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F. L. Stricklin, Jr., C. I. Smith, and F. E. Lozo

Report of Investigations—No. 71

BUREAU OF ECONOMIC GEOLOGY
The University of Texas at Austin
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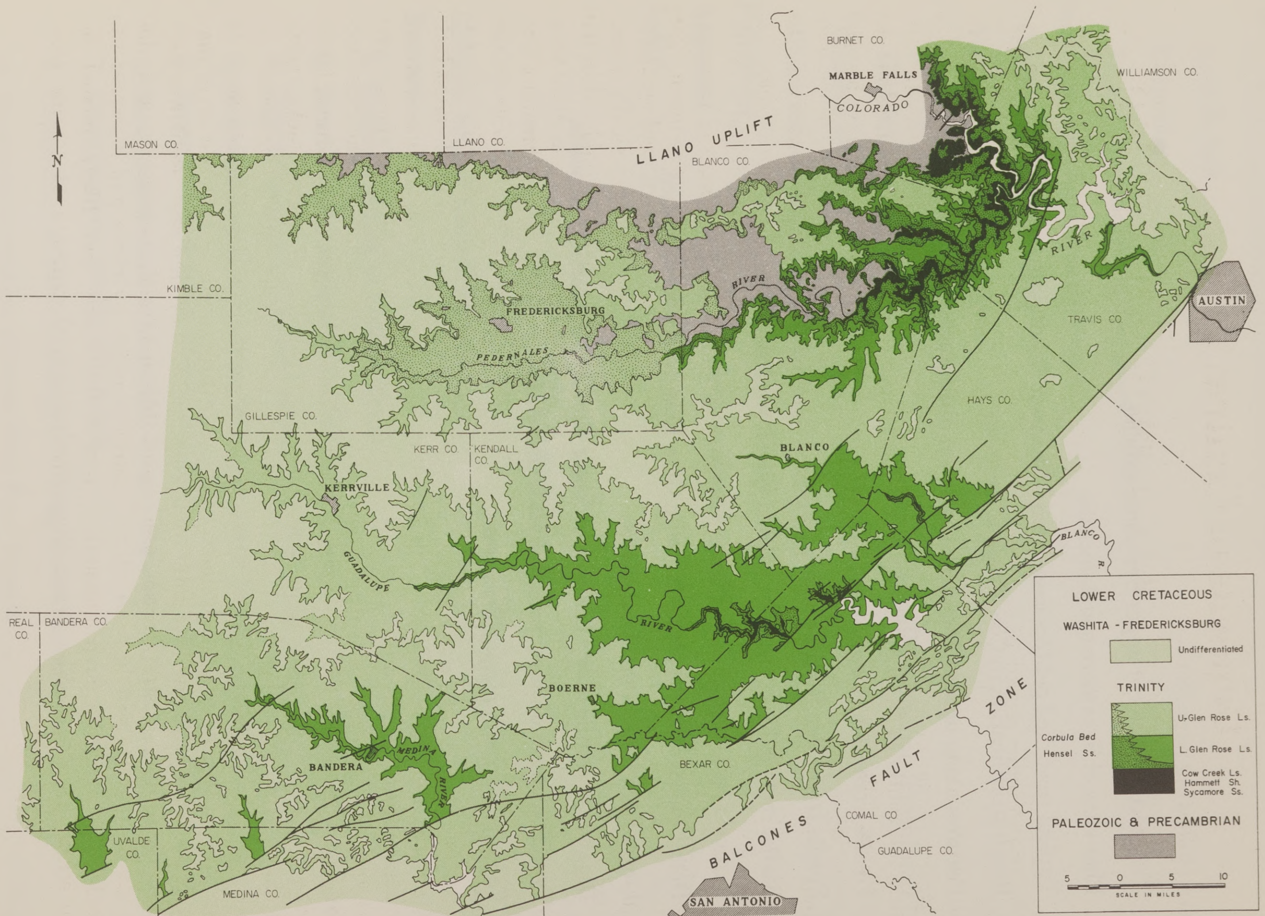

Geologic map of Central Texas

Stratigraphy of Lower Cretaceous Trinity Deposits of Central Texas[1]

F. L. STRICKLIN, JR.,[2] C. I. SMITH,[3] AND F. E. LOZO[4]

ABSTRACT

The stratigraphic record of the Lower Cretaceous Trinity Division in Central Texas, as revealed by extensive outcrop investigation, is that of a shallow sea transgressing the southern flank of the ancient Llano Uplift. This history is demonstrated by the overlap of marine carbonates on terrigenous facies representative of near-shore or onshore deposition and by sedimentary features indicative of various shallow-water environments of the marine shelf. Internally, the Trinity is comprised of three clastic-carbonate couplets, separated by disconformities, that reflect a pattern of cyclic sedimentation superimposed on the overall transgressive regimen. These couplets, made up of terrigenous formations overlain by carbonate formations, are regarded as lithogenetic time-stratigraphic units and are designated lower, middle, and upper Trinity. Formations constituting these Trinity subdivisions are, in ascending order of deposition, Sycamore Sand and Sligo Limestone, Hammett Shale and Cow Creek Limestone, and Hensel Sand and Glen Rose Limestone.

Trinity deposits are particularly illuminating from an environmental point of view because features of stratification and sedimentation are exposed in unusual detail. Included among the environmentally diverse strata are blanketlike beach deposits, rudist reefs, widespread tidal-flat deposits, shallow-water evaporites with an association of unusual diagenetic features, and shore deposits of caliche and alluvium. Of these strata, the beach and tidal-flat deposits are of prime importance because (1) they illustrate the diversity of environmental conditions which existed on the marine shelf, and (2) certain of their features allow interpretations of water depth, degree of water circulation, and morphology of the depositional environment. The faunas, bedding sequences, and sedimentary features which are genetically associated with these deposits should aid in the recognition of similar deposits elsewhere.

Among the numerous sedimentary features which have proved valuable in the recognition of Trinity depositional environments are sequences of cross-bedding, ripple marks, and organic features distributed along bedding surfaces. The latter include stromatolitic mounds and ridges of algal origin, clam borings, levels of bored pebbles, dinosaur tracks, mudcracks, and oyster shells cemented in growth position to bedding surfaces. If these features occur in a succession of marine beds, they indicate shallow-water, probably intertidal, deposition, and the surfaces bored by clams and incrusted by oyster shells are very likely related to brief subaerial exposure of marine sub-

[1] Shell Development Company, Exploration Production Research Report 525.

[2] Shell Oil Company, New Orleans, Louisiana.

[3] University of Michigan, Ann Arbor, Michigan.

[4] Shell Development Company, Houston, Texas.

strates and consequent hardening of sediments. On the other hand, if such borings and incrustations occur on top of continental sediments, they are associated with a disconformity and mark a former land surface transgressed by the sea.

The overall character of the Trinity and the nature of the land over which the transgression occurred indicate that a mild degree of land erosion favored the extensive deposition of low-to-high-energy bioclastic limestones along a shore of hummocky relief. This differs markedly from the setting of the modern low-lying Gulf Coastal Plain and its deposits. Except in some areas of very low land relief, such as along the Florida peninsula, the shelf today is being veneered predominantly by land-derived sediments.

INTRODUCTION

This report presents the descriptive stratigraphy of the Lower Cretaceous Trinity Division of Central Texas and offers interpretations of numerous sedimentary features of environmental significance. In addition, several stratigraphic intervals are described in detail and environmental models are reconstructed to account for their observed features.

The investigation underlying the report is one of a series of stratigraphic research studies undertaken by the authors and their associates for the purpose of defining stratigraphic principles and developing sedimentary models within a carefully constructed regional stratigraphic framework. It is believed that a regional approach to detailed stratigraphy not only markedly improves correlations and familiarity with rock types and sedimentary features but also increases the amount and quality of information derived when the models are extrapolated to other stratigraphic intervals. The Lower Cretaceous formations of Texas were selected for research study because of their extensive outcrops, good exposures of beds only mildly affected by tectonism, their wide range of represented depositional environments, and proximity to the Gulf Coast oil province where abundant subsurface information is available from most of the formations. Results of this and related studies have already been utilized in resolving problems related to exploration for Lower Cretaceous hydrocarbon reservoirs in the Gulf Coast and should prove equally useful for other geographic areas and stratigraphic intervals.

The area of investigation is confined to that part of Central Texas known as the "Hill Country"—an incised region encompassing several hundred square miles immediately south of the Llano Uplift and northwest of the low-lying Gulf Coastal Plain (fig. 1). This area is bracketed eastward and southward by the cities of Austin and San Antonio, where Trinity deposits are downthrown into the subsurface along the Balcones fault zone, northward by the Llano Uplift and its constituent Paleozoic and Precambrian rocks, and westward by the Edwards Plateau where Trinity deposits extend into the shallow subsurface beneath resistant carbonates of the Fredericksburg Division (*See* frontispiece). Within this area, the Trinity formations have been mapped and their stratigraphic relations have been determined by means of measured surface sections. These detailed sections constitute the basis for the report.

The subject matter around which the report is organized consists of the following broad topics: (1) stratigraphy of Trinity formations, with emphasis on lithology and boundary relations, (2) environmental interpretations of several confined stratigraphic intervals, and (3) broad conclusions regarding early Cretaceous sedimentation. The order of presentation followed in the report is that of the order of deposition of the several formations that comprise the Trinity.

Material contained in the report represents data collected and synthesized as part of a long-term stratigraphic research program undertaken by Shell Development Company. Of the authors, F. E. Lozo conceived, initiated, and directed the investigation from its inception in May 1953 until its termination in August 1959. During this entire time, F. L. Stricklin, Jr., was engaged in field operations and maintained headquarters in Kerrville, Texas; later, in May 1955, C. I. Smith joined the project in Kerrville and participated jointly in field work extending over an approximate four-year period.

During the course of the project, D. L. Amsbury and B. F. Perkins joined the stratigraphic research staff of Shell Development Company in Houston and contributed laboratory assistance in various

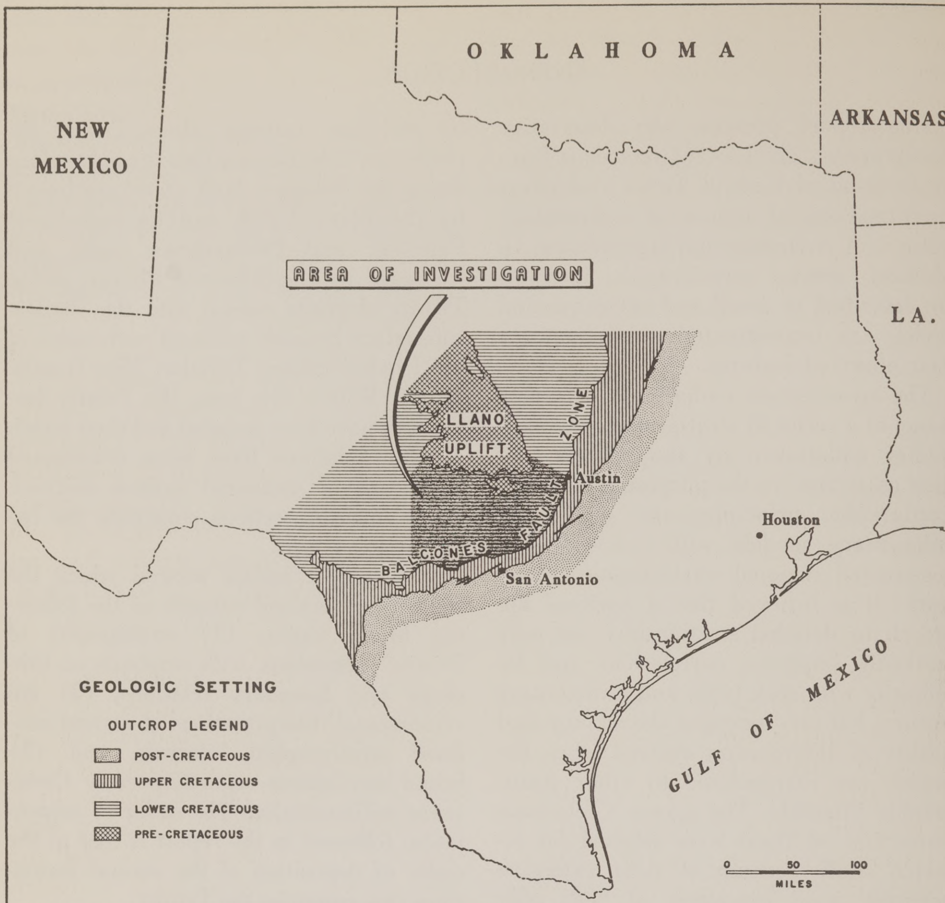

Fig. 1. Geologic setting of Central Texas.

phases of the project. The authors are indebted to Amsbury for details of rock types determined from petrographic analysis and to Perkins for the ecologic significance of particular fossils and faunal suites. Since the termination of this investigation several years ago, Amsbury and Perkins have added details on various facets of Trinity geology, and their specialized reports are in various stages of preparation for publication. It is hoped that this basic stratigraphic report will serve as an adequate background for the reports of these and other workers and that their studies will attain greater significance when considered in the light of the regional framework presented here.

PROCEDURES

The basic stratigraphic framework in the outcrop area was established with a regional grid of sections measured in detail with a hand level and steel tape at localities spaced rather evenly along depositional dip or strike. Careful discrimination was exercised in searching for fresh outcrops, and emphasis was placed on stream bluffs and channels subjected to the scouring action of intermittent floods.

Extreme care was followed in piecing together individual measured outcrops to construct composite sections showing weathering profiles and lithologic details: The general rule followed was to correlate stratal sequences and achieve a multiple match of individual beds. The resulting composite sections are shown in generalized form in cross sections that accompany the report. Individual sections are indicated by capital letters on the composite sections, and their localities are shown on a series of maps included in the Appendix.

Concurrent with the primary effort of measuring sections, additional efforts were directed toward gathering subsurface stratigraphic information. Core holes were drilled by Shell Development Company in various parts of the area, and additional cores obtained from related investigations were made available for inspection. Approximately 30 cores from depths of less than 200 feet were examined and described in detail. In addition, more than 100 electric logs ranging down to depths of 900 feet were obtained through the cooperation of landowners and water-well drillers by means of a portable Widco logger. The cores and electric logs obtained during the investigation provide valuable supplementary control in tracing and mapping sequences delineated in outcrops.

Beyond the initial effort to compile the gross stratigraphic framework for the investigated area, additional attention was focused on confined intervals of particular environmental interest. Four intervals representing diverse environments were studied in detail by measuring closely spaced sections and then specifically mapping facies changes, variations in thickness, distribution of diagnostic sedimentary features, and orientation of vectoral components of beds. These four investigated intervals include changes in rock type representing significant depositional or erosional events; hence this phase of the work added immeasurably to the understanding of geologic history.

RELATED INVESTIGATIONS AND ACKNOWLEDGMENTS

In the early 1950s, geologic studies were accelerated on the Cretaceous of Central Texas, both on the outcrop and in the subsurface. A number of oil companies conducted structural mapping programs north of the Balcones fault zone in connection with geophysical surveying for Paleozoic objectives. In the same area, severely affected by the drought of 1951–1957, water-supply investigations were supplemented by damsite studies and intensive water-well drilling activity. Downdip, the discovery of hydrocarbons in the "deep reef trend" increased interest in the subsurface Cretaceous. Coincident with the above, several organizations were concerned with carbonate rock research studies. Relevant data from these and other related investigations were materially significant in advancing the project study.

Compilation of the regional geologic map (frontispiece) was expedited with contributions of unpublished mapping by V. E. Barnes, Bureau of Economic Geology, in Burnet and Blanco counties; by J. R. Sandidge and Robert Pavlovic, Magnolia Petroleum Company, in Kendall and other counties to the west; by R. N. Holder, R. H. Stever, and J. S. Rives, Shell Oil Company, in Travis and Hays counties and the fault zone area to the southwest; and by H. G. Graham of Humble Oil & Refining Company in the upland area of Kerr and Kendall counties. This map information is to be incorporated in the Geologic Atlas of Texas project of the Bureau of Econmic Geology.

Concurrent with localized water-supply studies by W. O. George, F. C. Lee, F. A. Welder, and K. J. DeCook, of the U. S. Geological Survey, cooperative well logging materially added to the density of shallow subsurface data. Well cutting samples and copies of the Widco electrical logs obtained in the course of the project study have since been placed, respectively, in the Well Sample Library of the Bureau of Economic Geology and in the U. S. Geo-

logical Survey's Ground-Water Division files in Austin.

Critical to shallow subsurface control and precise identification of electrical log units were cores made available for study by the Corps of Engineers from Canyon Dam, by the San Antonio Water Board from test wells in the Canyon Lake reservoir area, and by the Guadalupe-Blanco River Authority from proposed damsites 7 and 8 upstream from Canyon Dam; other cores were supplied by Mason-Johnston & Associates in the Colorado-Pedernales drainage area. The damsite cores in Kendall and Comal counties plus those in Travis county (fig. 4) provided data basic to revision of Trinity classification and nomenclature (Lozo and Stricklin, 1956) and determination of proper outcrop correlatives (Lozo, Stricklin, and Schweighauser, 1956; Forgotson, 1956, 1957) of the subsurface Pearsall Formation (Imlay, 1945).

Company colleagues of varied backgrounds stimulated progress with penetrating discussions in the course of many field excursions. Throughout the investigation, mutually helpful information was freely exchanged among various company geologists and others engaged in related economic and academic activities, notably J. R. Sandidge, F. T. Johnston, D. E. Feray, H. F. Nelson, and Keith Young. Historically significant trips were personally conducted by the late F. L. Whitney and W. O. George. To V. E. Barnes, whose acute observations based on extensive field work anticipated many of the conclusions reached in this study, special appreciation is expressed for continued interest and total cooperation.

In the decade subsequent to the termination of this study, observations on various aspects of the Central Texas Trinity have been added by Barnes (1963–1967) in a new series of geologic quadrangle maps and by Young (1962, 1967a,b) in several excellent regional stratigraphic summations. Environmental reconstructions of the Glen Rose have been treated statistically by Behrens (1965) and in a less technical account by Nagle (1968). Petrographic and other details have been presented in unpublished University of Texas theses by Campbell (1962) on the Hensel Sand and on Trinity stratigraphic sections in the Guadalupe River valley by Cooper (1964) and Abbott (1966). To this list may be added the oral contributions presented with permission of Shell Development Company and recorded in abstracts by Perkins (1966, 1968) on rock-boring organisms and on a Glen Rose rudist-reef complex, and by Stricklin and Smith (1968) and Stricklin and Amsbury (1969) on environmental reconstruction and depositional models pertinent to the Cow Creek Limestone beach and Glen Rose shelf deposits, respectively.

REGIONAL GEOLOGIC SETTING

The Trinity formations discussed in this report were deposited on a southeastern, seaward-projecting flank of the Llano Uplift between the bordering East Texas and South Texas basins. Collectively, the formations comprise a wedge-like, overlapping sequence which abuts against older rocks of the Uplift and thickens from less than 150 feet in the northern part of the outcrop to more than 1,000 feet in the vicinity of the Balcones fault zone (fig. 2). Although equivalent formations in the adjoining basins are reported to be similar lithologically, thicker deposits accumulated in these subsiding areas (Adkins, 1933; Imlay, 1945; Forgotson, 1957; Winter, 1962).

The structure of the region is dominated by a promontory extending from the Llano Uplift southeastward across the Trinity outcrop area that is referred to as the San Marcos Arch (Adkins, 1933, p. 266). Probably initiated in Paleozoic time, this structural feature was a stable, positive element (relative to the bordering basins) throughout the Cretaceous Period, as indicated by reduced rates of sedimentation, maximum missing sections along unconformities, and facies changes within various formations (Adkins, 1933; Imlay, 1945; Durham, 1956, 1957). The configuration of the Lower Cretaceous shelf across the arch is reflected by isopach contours of Trinity deposits, by the outcrop and subcrop pattern of Paleozoic rocks which were part of the land mass, and, in a general way, by Trinity structural contours which probably approximate the original slope of the shelf, even though the beds have been tilted and faulted (fig. 3). All these characteristics suggest that the depositional and structural setting of the Lower Cretaceous shelf was pre-determined by the ancestral Llano Uplift.

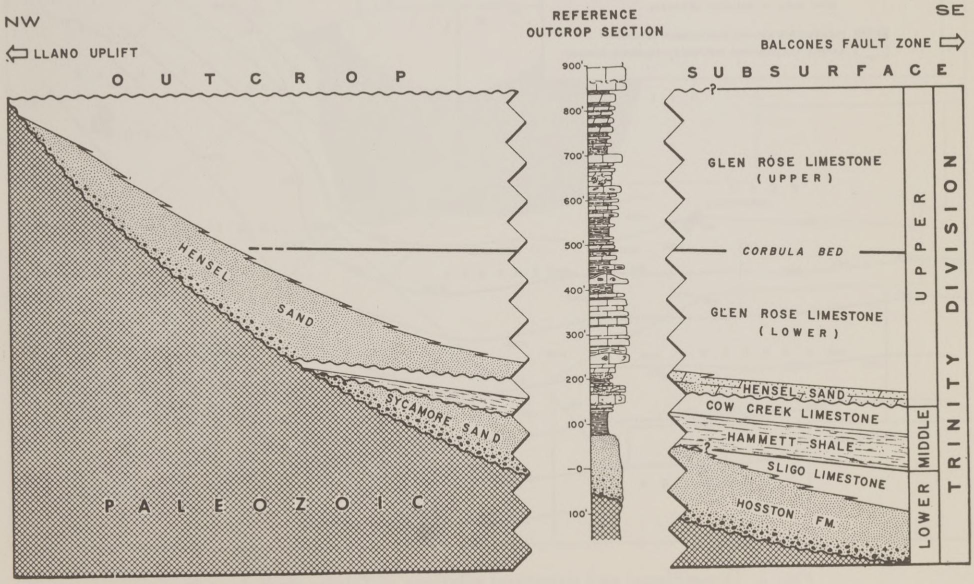

FIG. 2. Stratigraphic diagram of the Trinity Division.

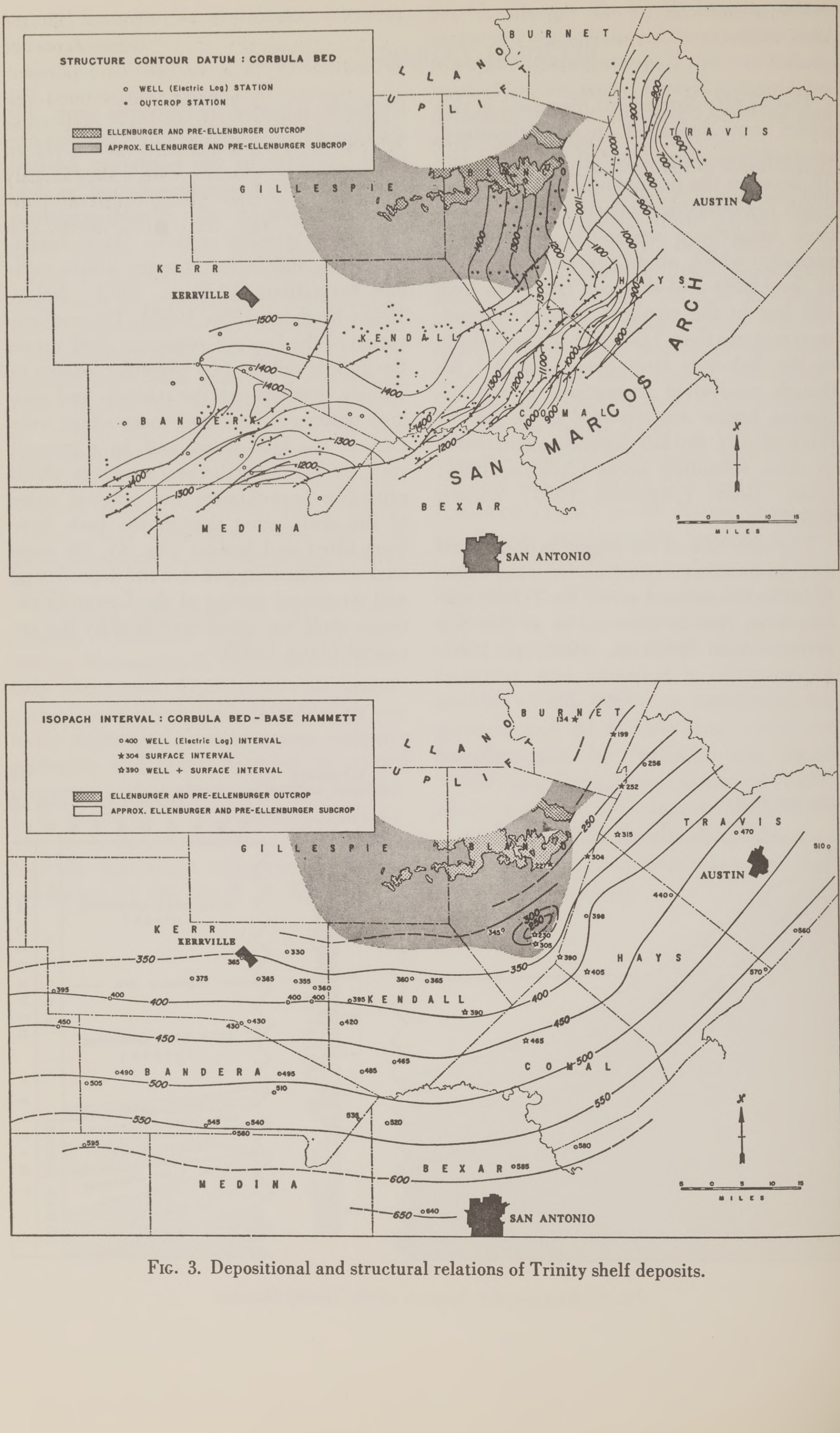

Fig. 3. Depositional and structural relations of Trinity shelf deposits.

Facies analyses indicate that the Trinity shelf was a site of primarily shallow-water deposition and was frequently exposed subaerially during regressions and low sea stands. Rudist and coral reefs, intertidal beds and associated evaporites, and beach deposits are the most obvious evidence for shallow-water deposition. The evidence for interruptions in deposition, which resulted in several unconformities and numerous diastems, is contained in repeated occurrences of diagnostic sedimentary features related genetically to subaerial exposure of sediments. In gross lithologic perspective, the Trinity is composed of fine terrigenous clastics and marine carbonates which thin landward and are replaced along updip edges by redbeds shed largely from the ancestral Llano Uplift and deposited near the shore of a northward-encroaching sea.

The formations which constitute the Trinity Division of Central Texas (fig. 2) are genetically combined as partially equivalent terrigenous clastic-marine carbonate couplets separated by disconformities. The couplets, referred to as lower, middle, and upper Trinity, vary from less than 100 to almost 1,000 feet in thickness, and each corresponds to a single transgressive-regressive cycle of sedimentation. In depositional order, the formations that comprise the couplets are the Hosston Sand and Sligo Limestone, both represented at the outcrop by the Sycamore Sand; the Hammett Shale and Cow Creek Limestone; and the Hensel Sand and Glen Rose Limestone.

The genetic associations indicated above represent the third in a progressive series of Trinity classifications based on the observed or inferred gradational relationship of clastic units with overlying carbonate intervals. The original single-cycle concept of Hill (1891–1892, 1901) was revised by Barnes (1948) with the recognition of two cycles; the three-cycle concept (Lozo and Stricklin, 1956) is an extension of Barnes' revision with certain differences in matters of nomenclature.

Hill's pioneer classification derived from J. A. Taff's details in the Colorado River valley outcrops in the course of Cretaceous investigations under Hill's direction for the Geological Survey of Texas. Hill (1891, 1892) expanded the Trinity Division from its earlier restriction (1889, 1890a,b) to the basal Cretaceous sand section [Upper Cross Timbers Formation or Trinity sands] to include the overlying Glen Rose limestone beds. Subsequently, the sub-Glen Rose sandy Trinity beds of Taff's (1892) Hickory Creek section were designated as the type Travis Peak Formation (Hill and Vaughan, 1898), later to be subdivided into the Sycamore sands, the Cow Creek beds, and the Hensell [sic] sands as members (Hill, 1901). The Glen Rose–Travis Peak boundary was clearly recognized as transitional, and the two formations were considered as distinctive facies of an uninterrupted depositional series. Hill's classification was applied by most workers over the next half century; the nomenclature of 1901 remains as official usage of the U. S. Geological Survey.

Hill's concept prevailed, with the exception of Cuyler's (1931, 1939) speculation on a disconformity with onlap at the base of the Glen Rose, until Barnes (1948) emended the Travis Peak by emphasizing the sharp aspect and mappable utility of the upper limit of the Cow Creek Limestone, the presence of locally developed basal conglomerates in the Hensell [Hill's misspelling retained], and the transitional nature of the Hensell–Glen Rose contact. These points, from extensive field observations in the Pedernales–Colorado drainage area, were major considerations in pairing the Sycamore [including the overlying shale = Hammett] with the Cow Creek Limestone as the emended Travis Peak Formation, and the Hensell Sand with the Glen Rose Limestone as members of the newly proposed Shingle Hills Formation. This two-cycle concept of the Trinity was applied to mapping projects of the Bureau of Economic Geology in Gillespie, Blanco, Burnet, and western Travis counties in a series of guidebook (Barnes, 1949, 1951, 1958) and quadrangle map publications (Barnes, 1952–1956 and 1963–1967).

The three-cycle concept here applied to the Trinity developed with recognition and definition of the Hammett Shale (Lozo and Stricklin, 1956) as a distinctive formation unit, evaluation of the Hammett–Sycamore contact as a disconformity, and realization that the Hammett Shale, in its genetic relationship to the overlying Cow Creek Limestone, was analogous to the Hosston Sand–Sligo Limestone sequence below and the Hensel Sand–Glen Rose Limestone couplet above. Subsequent to Hill's (1901) original assignment of this [Hammett] shale as a lower part of the type Cow Creek beds, as pointed out by Damon (1940) after Cuyler (1939) included the unit in the Sycamore by restricting the term Cow Creek to the overlying limestone only, the Hammett (as upper Sycamore) was essentially ignored until Barnes (1948) noted the mappable nature of a color change associated with a horizon of pholad-bored carbonate pebbles and boulders at the base of the unit. Barnes later (1951) advocated a return to Hill's usage of Sycamore, not that of Cuyler and several others (Imlay, 1945; George, 1947, 1952; Cloud and Barnes, 1948; and DeCook, 1960); the revised position of the Cow Creek–Sycamore boundary did not alter Barnes' two-cycle concept of the Trinity (Young, *in* Stenzel, 1953; Barnes, 1953).

Although this report is concerned primarily with the outcrop and shallow subsurface area of the Trinity north of the Balcones fault zone, it may be noted that the three-cycle concept was a direct outgrowth of indications—based on preliminary attempts to relate outcrop units to those of the subsurface south of the fault zone—that Imlay (1944, 1945) incorrectly equated the type Travis Peak Formation with the subsurface Pearsall Formation. Specifically questionable were assignments of the lower and upper Pearsall shale members, respectively, as outcrop Sycamore and Hensell [sic] sand correlatives. These questions were resolved early in 1953 with study of damsite cores in Kendall County (Guadalupe–Blanco River Authority Damsite No. 7, north of Bergheim at Schillers Crossing). The post-Sligo/pre-Hensel sequence in the damsite cores was clearly recognizable as the post-Sycamore/pre-Hensel section of the unnamed shale [Hammett] and overlying Cow Creek Limestone of the type Travis Peak area to the northeast. These units could be tied directly by well samples and electrical logs into the type Pearsall (Imlay, 1945) of Frio County with secure determinations of the lower Pearsall shale (Pine Island Member) and middle Pearsall limestone (Cow Creek Member); the absence of the upper Pearsall (Hensell Shale Member of Imlay = Bexar Shale of Forgotson, 1956) in the Guadalupe damsite and type Travis Peak areas was attributed to non-deposition or truncation. These revisions, summarized by Lozo, were included in an open-file report of June 1953 prepared for the Guadalupe-Blanco River Authority by Mason-Johnston & Associates, geological consultants; they were reviewed in a pre-field trip panel discussion of March 1955 for the Corpus Christi Geological Society, were presented orally in detail at the XX International Geological Congress, September 1956 in Mexico City,[4] and were published in abridged version in the Gulf Coast Association of Geological Societies Transactions (Lozo and Stricklin, 1956). With minor differences of opinion on correct spelling (Hensel vs. Hensell), choice of nomenclature (Pine Island or Hammett, Shingle Hills Formation or upper Trinity subdivision), and preference of classification (Sligo and Hosston = Coahuila Series or Comanche Series), the basic stratigraphic relationships presented here are in general agreement with those of Forgotson (1956, 1957), Barnes (1956, 1958, and *in* Bell, Cloud, and Barnes, 1962), Amsbury (1962), Tucker (1962a, b), and Young (1962, 1967a, b).

LOWER TRINITY

The lower Trinity is divided into two formations: the basal Sycamore Sand (subsurface Hosston Sand) and the overlying Sligo Limestone, which is entirely subsurface and subcrops beneath the southern part of the investigated area (fig. 4). Outcrops of the Sycamore are restricted to the drainage basins of the Colorado and Pedernales Rivers, west and northwest of Austin (fig. 4), and are the most limited in areal extent of all the Trinity formations.

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[4] This paper, scheduled for the third volume of the Cretaceous Symposium, remains unpublished due to exhaustion of I.G.C. funds. The abstract (Lozo, Stricklin, and Schweighauser, 1956) is in the Resumenes . . ., XX Congreso Geologico Internacional, pp. 334–335.

FIG. 4. Regional map showing distribution of lower Trinity deposits.

Lithologic Character

Sycamore Sand.—The Sycamore within its outcrop areas rests unconformably on folded Paleozoic rocks, usually Smithwick Shale or Marble Falls Limestone (Pennsylvanian), and thins northward to a feather edge from a maximum surface thickness of approximately 100 feet. The formation is comprised of an irregularly bedded sequence of predominantly red conglomerate, sandstone, and claystone, but the most abundant single constituent is quartz sand. Though there is much local diversity in grain size, there is an overall gradation from coarse to finer, both upward from the base and laterally in the direction of thickening. Boulders ranging up to 1 foot in diameter are common updip. These lithologic characteristics plus the presence of lenticular channel deposits through much of the outcrop area indicate the Sycamore to be an alluvial sequence deposited by aggrading streams. In addition to pebbles and boulders derived from Paleozoic sedimentary rocks and older igneous and metamorphic rocks of the Llano Uplift, detrital dolomites with overgrowths on original rhombs are present (Amsbury, 1962), as are glauconite grains of probable second-cycle derivation from Cambrian deposits. Damon (1940) reported glauconite locally in the upper Sycamore and interpreted it to be of authigenic marine origin, but an alluvial origin of reworked grains seems to be more consistent with other properties of the Sycamore.

One of the most interesting facies of the Sycamore is seen in irregular lentils of caliche found in some exposures at the top of the formation along the Pedernales River, Blanco County (fig. 4). The caliche is several feet thick and contains oolites, pisolites, and siliceous grains and pebbles enclosed in a fine-grained carbonate matrix with numerous crinkly laminations (Pl. I). Other characteristics of the caliche and evidence for its origin are discussed in a later section dealing with criteria distinguishing an unconformity developed on lower Trinity deposits.

Sligo Limestone.—The Sligo Limestone, at least in part age equivalent of the Sycamore Sand through downdip facies change, contains miliolids and oolites as its most distinctive components and was deposited in a shallow sea that approached but never reached the area of lower Trinity outcrops. Since the Sligo does not crop out here, nor elsewhere within the United States, details on stratigraphy are provided only by cores and cuttings.

According to a detailed analysis of several cores by David Amsbury (personal communication, 1967),[5] the Sligo limestone grades transitionally into the underlying alluvial Sycamore Sand and consists of two gross facies: (1) a lower unit of laminated dolomite, siltstone, and gray lime mudstone and wackestone and (2) an upper unit of oolith lime packstone and grainstone. The latter unit, as developed in cores from Guadalupe–Blanco River Damsites 7 and 8 and from Stanolind No. 1 Schmidt (fig. 4), is dolomitized 35 feet below its top, contains numerous burrows that obliterate or obscure the original bedding, and is typified by quiet- and agitated-water deposits marked respectively by unbroken shells and reworked fossils and oolites.

The Sligo thickens markedly downdip from its updip facies pinch-out. It is 78 and 96 feet thick, respectively, in core borings at Guadalupe–Blanco River Damsites 7 and 8, Kendall and Comal counties, and expands to more than 220 feet thick in Pan American No. 1 Schmidt, Guadalupe County. Together with the underlying Sycamore, or the Hosston Formation as the equivalent is termed in the subsurface, the clastic-carbonate couplet reaches a thickness of more than 900 feet in eastern Travis County (fig. 5).

[5] A report by Amsbury entitled "Stratigraphic Petrology of the Lower and Middle Trinity Rocks in South-Central Texas" is in an advanced stage of preparation for publication by The Geological Society of America.

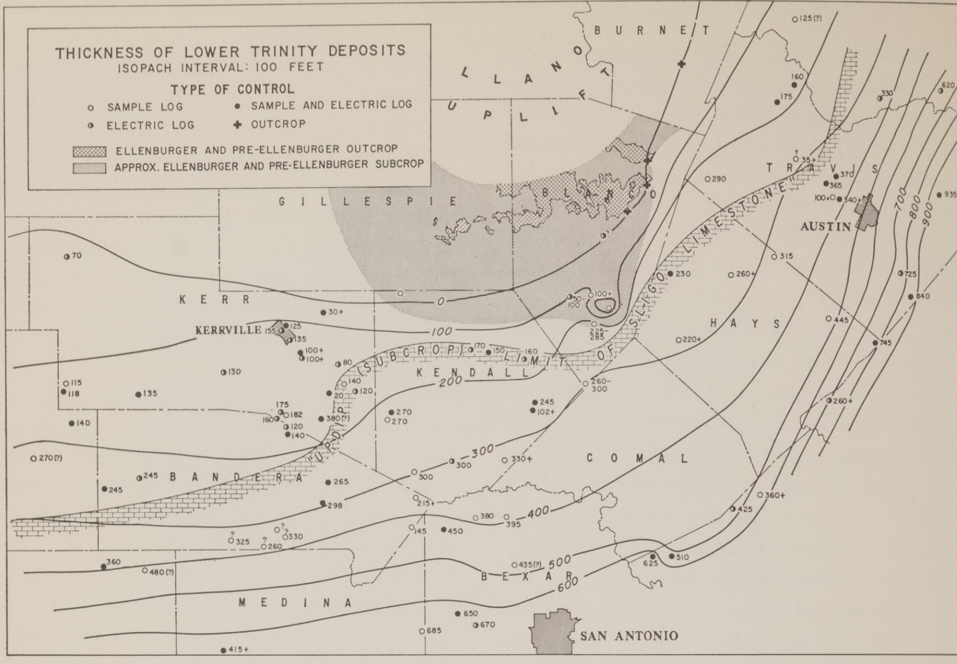

Fig. 5. Isopach map of lower Trinity deposits.

Depositional Environments

The general lithologic character of the Sycamore and its many indications of stream channels within the outcrop area are considered to be evidence of a piedmont or valley-fill type of deposit. Other than the misleading occurrence of glauconite, there is no suggestion of a marine origin for these redbeds. However, the vertical reduction in size of components reflects a marine transgression that approached but did not reach the outcrop area, and a progressive reduction of stream gradients during Sycamore deposition. Downdip in the subsurface, where the Sycamore or Hosston grades transitionally into the Sligo, some of the sands probably were deposited in brackish waters of an advancing sea. The two dominant facies of the Sligo, according to Amsbury, record a progressive landward migration of bay, lagoonal, and high-energy marine sediments over alluvial deposits of the Sycamore. Finally, the depositional cycle represented by the Sycamore and Sligo ended with a relative drop in sea level, and lower Trinity sediments throughout most of the investigated area were exposed to weathering processes and cemented prior to deposition of the marine Hammett Shale.

Nature and Significance of Upper Boundary

The Sycamore and Sligo are overlain disconformably by the marine Hammett Shale. The relation of the Hammett to the underlying distinct surface of erosion is one of marine onlap, because successively younger Hammett beds rest on the surface of disconformity progressing in an updip direction (fig. 6). This accounts for much of the updip thinning of the Hammett and reflects a steady landward shift of deposition as the sea encroached upon weathered lower Trinity deposits.

Evidence of weathering.—The caliche, developed locally at the top of the Sycamore in Blanco County (fig. 4), apparently records a period of calcareous soil

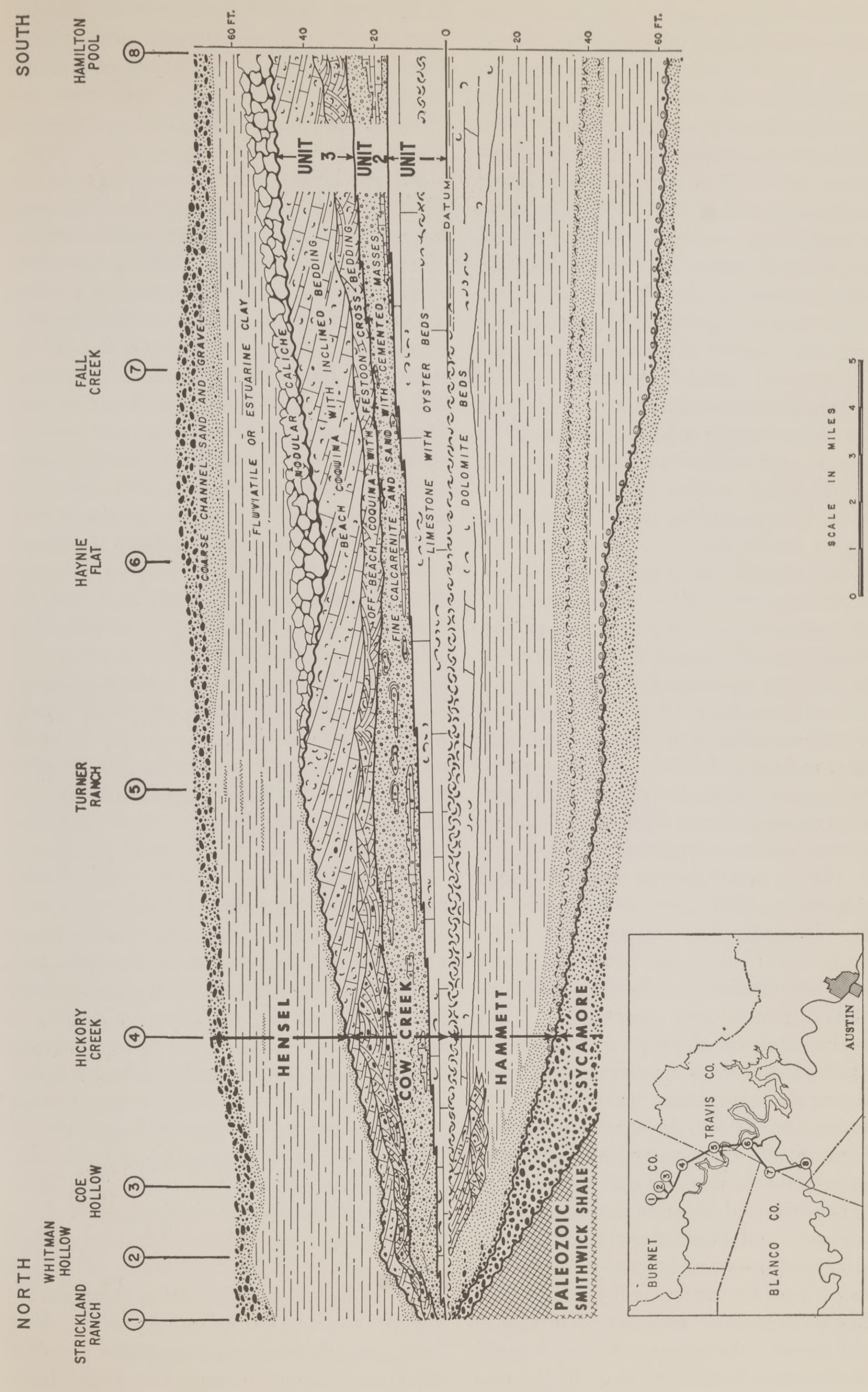

FIG. 6. Stratigraphic section of middle Trinity deposits.

formation produced in an arid climate. Distinctive features of the caliche are an unusual admixture of oolites and scattered siliceous grains and pebbles in a fine-grained limy matrix (Pl. I). The oolites are poorly sorted and display distinctive rings in cross section—in some cases as many as five or six—and no fossils have been observed within the nuclei. The associated pebbles are unevenly distributed and range up to 2 inches in diameter; many are surrounded by closely packed oolites and some display laminated, travertine-like overgrowths which commonly flare outward into basal pedestal structures (Pl. I). Crinkly laminations also occur throughout the limestone where pebbles are not present. Veins and pockets of calcite are common, and relict cavities floored by oolites and finer internal sediment and filled above by sparry calcite have been observed.

Several significant features of the caliche, namely, the oolites themselves and their closer concentration around pebbles, the travertine-like pedestal structures beneath pebbles, the abundant calcite veins, and the cavities floored by oolites, are best explained as solution-and-deposition features produced by downward-seeping ground water. A similar caliche with concretionary oolites, pisolites, and laminar structures occurs as a Pliocene soil on the High Plains and like the caliche under consideration, also caps a fluviatile sequence (Swineford, Leonard, and Frye, 1958, p. 98); both the concentric and laminar structures within the Pliocene Ogallala limestone are reported (p. 115) to be the result of repeated accretions left on grains and irregular surfaces by downward-percolating ground waters enriched with calcium carbonate through surface evaporation. These properties leave little doubt as to subaerial alteration of Sycamore deposits and indicate that the caliche is not preserved as erosional remnants of Sligo Limestone as was first suspected because of the presence of oolitic limestone at this stratigraphic position. The alteration of the initial Sycamore deposits could have taken place during either of the two known periods of subaerial exposure: the modern one or that during the Lower Cretaceous prior to advance of the middle Trinity sea. The latter period is implied by the absence of similar limestone developed elsewhere within the modern soil zone.

Physical character of erosion surface.—The surface of disconformity developed on lower Trinity deposits is an initial surface of subaerial dissection modified by wave and current erosion of the middle Trinity sea. Several features of the surface identify it as a former marine substrate. It has low relief, usually only a few inches locally, and associated pebbles and boulders are locally beveled to form a relatively smooth pavement, as is apparent in Plate II. This mode of erosion indicates that the conglomerate was well cemented prior to marine transgression. In addition to these physical erosion characteristics, the surface of disconformity is locally dotted by small pits made by boring clams (Pl. II), contains scattered incrustations of oyster shells, and is overlain by loose pebbles and boulders which are also pitted by clam borings (Pl. III). These organic features which aid the recognition and interpretation of this disconformity and numerous diastems in upper Trinity deposits are discussed as follows.

Close inspection of the small, flask-shaped pits along this disconformity and in the associated pebbles and boulders usually provides the key to their origin and significance, as previously reported by Perkins (1966). Some pits usually display a heart-shaped outline of the clam bivalves; in some cases, the original shell is preserved as a pit lining and in other cases the shell has been leached away, leaving casts in pits just beginning to develop. A few of the latter, which have been extracted from bored boulders overlying the surface, show the size and shape of the clam and details of the bivalve attachment area (Pl. III). Thin sections of the pits usually reveal abrupt termination of some rock grains flush with the pit wall; therefore, the pits are the result of a boring clam rather than one that burrowed by shoving sediment particles aside or ingesting them. The mechanism of such an implied boring operation requires a firm or lithified surface.

Selective distribution of the borings is apparent where the surface is developed on conglomerate, because pebbles of quartzite, chert, and sandstone are characteristically devoid of pits, whereas those of dolomite and limestone are extensively bored. This preferential distribution of pits may have been caused by either of two methods of boring. Observations by Younge (1951, pp. 163–165) reveal that modern rock-boring clams live just beneath a firm, or hard, marine substrate; some species bore into the sea floor by dissolving the rock with body acids, and others by removing the rock with a grinding or pressing action of the valves, using the shell itself as an abrasive. The specific method by which clams bored into all but the siliceous Sycamore rocks of the marine substrate has not been determined.

Bored pebbles and boulders (Pl. III) characterized by the same kind of pits are spread along the surface of disconformity as erratics encased in the overlying Hammett Shale. This veneer of pebbles was first reported by Barnes (1948, p. 8) and used as one of the identifying characteristics of a mapping horizon. The pebbles and boulders are composed mostly of Ellenburger dolomite and are usually rounded and bored on all sides, suggesting reworking and overturning by waves and currents. Dimensions are commonly 2 or 4 inches, but diameters ranging up to 1 foot have been observed. Unbored siliceous pebbles are also present. The specific mode of distribution of these pebbles over an area of several hundred square miles and at the base of quiet-water shale is unknown, but a likely speculation is that they are lag residue resulting from subaerial erosion of the Sycamore and winnowing by marine erosive agents accompanying transgression of the sea prior to deposition of the Hammett Shale.

Oyster shells attached to the surface of disconformity are also common. Like bored surfaces and pebbles, these indicate marine inundation of firm or lithified materials, because oyster spats require firm surfaces for attachment.

The onlap of marine beds upon the continental Sycamore identifies this disconformity as a geologically significant horizon marking a marine transgression over terrane of gentle slope. Negligible land-derived sands or coarser clastics were deposited in the edge of the advancing sea; otherwise, the Sycamore and Hammett would appear transitional, and marine organisms could not have been in contact with the erosion surface. This transgression marked the beginning of a new cycle of Lower Cretaceous deposition—that of the middle Trinity.

MIDDLE TRINITY

The middle Trinity formations comprise a marine wedge no more than 120 feet thick at the outcrop and include a basal shale, named Hammett as an outgrowth of this investigation (Lozo and Stricklin, 1956, p. 69), and the overlying Cow Creek Limestone (fig. 6). Complete sections of both formations occur only along the Colorado and Pedernales Rivers, but partial exposures of the Cow Creek are also present southward along the Blanco and Guadalupe Rivers.

Lithologic Character

Hammett Shale.—The Hammett is composed primarily of dark calcareous or dolomitic shale which expands from its updip pinch-out to more than 60 feet thick in the outcrop (fig. 6) and continues downdip into the subsurface as a blanketlike deposit of gradually increasing thickness. From the authors' experience in working with electric logs and other subsurface data, the Hammett and equivalent Pine Island Shale of the East Texas basin are one of the most persistent lithologic units within the Lower Cretaceous of Texas. The geographic extent of the Hammett, its marine microfauna, and the lateral continuity of some beds indicate that the shale is genetically associated with a widespread marine transgression.

Microfossils from several Hammett cores have been investigated by Jacob Schweighauser. From the fauna in a core from the type locality (locality 8, fig. 6), Schweighauser (personal communication, 1956) noted both arenaceous and calcareous forms. Arenaceous forms, including *Ammobaculites, Haplophragmoides, Trochammina, Verneuilina-Gaudryina, Dorothia,* and *Marssonella*, range throughout the shale; calcareous forms, such as *Lenticulina, Vaginulina,* and *Citharina*, are restricted in occurrence to a few feet at the base and top of the Hammett and to a 10-foot interval just below the middle. According to Schweighauser, these sporadic occurrences of a calcareous fauna possibly represent less turbid conditions on an open sea floor.

Other rock types of the Hammett include redbeds and a local limestone facies updip and, farther downdip, sand beds near the middle and dolomite at the top (fig. 6). The limestone facies is of special interest, because it contains two cross-bedded sequences of coquina in the Coe Hollow area that appear to be a result of beach accretion. These deposits will not be elaborated upon, but their similarity to Cow Creek beach and off-beach deposits as described in the following discussion should be borne in mind.

Cow Creek Limestone.—The Cow Creek, a sequence of bioclastic limestones, expands rather uniformly southeastward from its pinch-out edge to a downdip surface thickness of about 60 feet. In the northern outcrop area, it is divisible into three stratigraphic units, as shown in figure 6: Unit 1, horizontally bedded, fine to coarse-grained calcarenitic limestone; Unit 2, silty calcarenite with concretionary masses and fine quartz sand; and Unit 3, cross-bedded coquina of coarse shell fragments in a sparry matrix, with poorly sorted quartz grains and scattered siliceous pebbles. Individual beds within these units are traceable for short distances only. In outcrops southward along the Guadalupe River, these units have not been differentiated, and the Cow Creek is primarily fine- to medium-grained calcarenite comprised of well-rounded shell fragments with common thin oolitic coatings. Of the wide variety of fossils in the Cow Creek, oysters and other pelecypods are by far the most abundant.

Beach Stratification of the Cow Creek

The upper beds of the Cow Creek (Unit 3) are of particular environmental interest because they comprise an offlapping sequence of beach deposits built out from a shoreline of early Cretaceous and Paleozoic rocks (Stricklin and Smith, 1968). These beds display the relict morphology of the ancient shoreline and adjacent sea floor in obvious detail and are submitted as one of the best examples of beach deposits in the geologic literature. The Cow Creek beach deposits comprise a tabular rather than a linear body in the perspective apparent from the outcrop, and unlike most beach accumulations along continental margins, they are composed primarily of carbonate detritus rather than quartz sand. Oyster shell coquina is the principal component.

The beach deposits display three types of cross-bedding that are representative of the typical beach profile (fig. 7). Festooned cross-beds at the base of Unit 3 are identified with an uneven off-beach slope, uniformly inclined beds in an intermediate position are associated with a smooth foreshore (Pl. IV, B), and similar but oppositely inclined beds developed locally at the top of the sequence are apparently those of the backshore (Pl. IV, A). These three types of cross-bedding are ideally displayed along the channel of Cow Creek, the namesake locality of the formation, approximately one-half mile downstream from the farm road crossing to the Hensel ranch house, northwestern Travis County. Additional details on these cross-bedding types and respective interpretations are discussed as follows.

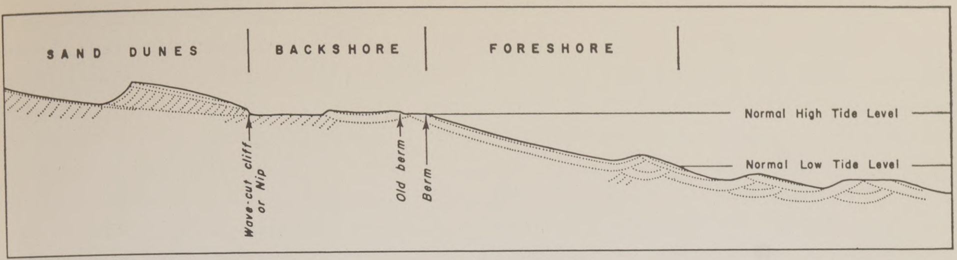

FIG. 7. Diagrammatic profile of a beach. (After Dunbar and Rodgers, 1957.)

Off-beach beds.—The festooned cross-beds at the base of the beach sequence are evidently the current deposits of an off-beach zone of vigorous scour and fill. A succession of these beds shows much irregularity in stratification, but individual festoon accumulations display garland-like or crescent-shaped patterns in both vertical and plan view. These properties are consistent with descriptions of festooned cross-bedding by Knight (1929, pp. 56–74). Knight (1930, p. 86) attributed the formation of such beds to an orderly process of scour and fill dominated by the following events: (a) scouring of plunging, elongate, ellipsoidal troughs followed by (b) filling of the troughs by laminae concordant with the trough floor, and finally (c) partial truncation of the laminae by later scouring. Apparently, current-driven sediment waves are responsible for the scour-and-fill sequence of events indicated by such cross-bedding, and it seems likely that the sediment waves may be either continuous in the form of irregular ripples or broken into individual barchans. In either case, however, the resulting sediment-filled troughs should be oriented in the direction of current flow with the beds showing a dominant downcurrent component of dip. Following this interpretation, close agreement in the orientation of Cow Creek troughs suggests that currents flowed dominantly in a southwesterly to westerly direction, but a few troughs have an opposing alignment. This would imply longshore currents and counter-currents, a circulatory condition common along modern beaches. Hulseman (1955) reported some festoon troughs in the North Sea with axes parallel to the shoreline and oriented in opposing directions; the bimodality of these troughs is related to incoming and outgoing tides.

Elsewhere, at Galveston Beach, Texas, the authors have observed longshore currents and counter-currents flowing simultaneously in different depth zones of the beach profile or alternating during various periods of the day. Hydrographic data from the Gulf of Mexico, as summarized by LeBlanc and Hodgson (1959, p. 201), indicate seasonal reversals of dominantly westward-flowing surface currents off Galveston Island during the months of July and August.

Foreshore beds.—Beds of essentially parallel inclination comprise a unit of variable thickness in the middle of the beach sequence that usually does not exceed 12 feet (Pl. IV, B). Individual beds are ordinarily less than 1 foot thick, are separated by well-developed bedding planes, and constituent layers of coquina are crudely laminated. The beds maintain an average inclination of about 7 degrees and vary only slightly from a southeasterly to southerly dip direction. From this evidence, these inclined beds and their constituent laminae are inferred to be successive accretions of a smooth, relatively steep foreshore along a southwesterly to westerly trending shoreline. Since the accretions do not constitute a linear body, but rather one of blanketlike dimensions, extensive seaward growth of the beach over at least 25 miles is indicated (fig. 6).

Accessory components in the foreshore

and underlying off-beach cross-beds include coarse terrigenous sand, land-derived pebbles of varying size and composition, and local occurrences of whole fossils. The terrigenous fraction comprises 20 to 35 percent of the beds and gradually grades from dominantly coarse quartz sand downdip to coarse chert and quartz gravels updip. Sizes of the latter rarely exceed 1 inch downdip but are commonly 2 to 4 inches near the landward pinch-out of the Cow Creek. Typically admixed with the updip gravels are large pebbles and boulders of Ellenburger dolomite, which commonly display pholad clam borings, and scattered pebbles of Smithwick shale. A striking local component in the vicinity of Coe Hollow (fig. 6, locality 3) includes large, apparently reworked coral heads ranging up to 1 foot in diameter. The growth site of these corals, which are considered unusual because of their proximity to the Paleozoic landmass and their association with coarse terrigenous gravel, is unknown but may be related to a compactional topographic high possibly developed above nearby local beach deposits (fig. 6, locality 3) in the underlying Hammett Shale. Additional whole fossils locally present throughout the extent of the beach deposits include the clams *Trigonia* and *Protocardia?*, which are commonly associated with bedding planes.

The character of modern beaches is primarily a function of wave action. According to Thompson (1937, pp. 728–729), who made an intensive investigation of the origin of California beaches, the foreshore slope is continually being modified by an ever-changing combination of variable factors, probably the most important of which are the size and direction of approach of waves, tidal variations which cause the zone of wave action to shift back and forth, and the character of material available for transportation and deposition. Foreshore deposits of the Cow Creek show local variations in size of components and dip that seem to be consistent with such changing conditions.

Backshore beds.—The beach sequence is terminated vertically in some downdip localities by beds that dip gently away from what appears to be a beach crest or berm (Pl. IV, A). Because the dip of these beds is opposed to that of the underlying foreshore deposits, they appear to be backshore beds deposited on a surface of beach erosion. Similar opposing dips of foreshore and backshore beds are reported by McKee (1957, pp. 1707–1718) from several beaches along the Pacific coast of California and Mexico and at Mustang Island, Texas, bordering the Gulf of Mexico. Scattered intact shells of clams and ammonites indicate that the Cow Creek backshore deposits are not as thoroughly reworked as those of the foreshore, implying that they are possibly storm deposits flung up by unusually large waves and buried on higher parts of the beach. As such, these backshore deposits are the final additions to a sequence which represents the conversion of sea bottom to land by seaward-shifting beach zones of sedimentation.

Nature and Significance of the Upper Boundary

The Cow Creek Limestone is overlain disconformably by non-marine Hensel deposits. Successively younger Cow Creek beds lie beneath the surface of disconformity in a downdip direction as a result of seaward progradation of the beach, and erosion or weathering of abandoned beach segments is implied. The surface of disconformity developed on beach deposits of Cow Creek is one of slight but irregular topography (Pl. V, A). Where the surface has been stripped of the overlying Hensel, it displays irregular knolls and depressions and superficially resembles a tract strewn with large boulders (Pls. V, A and VI, A). Such disorderly topography does not suggest the integrated drainage of a stream and a resulting planated or incised surface but rather erosion by other means commonly observed on modern beaches. Apparently, this topography has resulted from a combination of dissection and shifting of unconsolidated backshore sediments by storm waves and solution of a limy terrane by infiltrating ground water. Wind erosion and deposition may have been additional complicating factors because in some places the beach deposits are overlain by calcareous mounds containing shell fragments (Pl. V, B). It appears very likely that these mounds originated as eolian dunes of sediment swept from the underlying Cow Creek deposits.

The Cow Creek disconformity differs physically from that at the base of the middle Trinity, as summarized in figure 8, and has quite different geological implications. The disconformity at the base of the Hammett signifies marine transgression and onlap, and that at the top of the Cow Creek denotes marine regression and offlap of the beach beds. Thus, middle Trinity deposits represent a complete cycle of sedimentation.

UPPER TRINITY

The upper Trinity formations are the Hensel Sand and the overlying Glen Rose Formation (fig. 2). The Glen Rose is the thickest and most extensively exposed of all Trinity formations and is separable into upper and lower members of differing lithologic characteristics by the *Corbula* bed, a widespread marker datum initially recognized by F. L. Whitney. The Hensel is a single, time-transgressive lithologic unit comprised primarily of alluvial and near-shore marine sands equivalent to Glen Rose deposits (fig. 2). The Hensel and Glen Rose Formations constitute a massive wedge which thins from about 1,000 feet near the Balcones fault zone to less than 50 feet at the updip edge near the Llano Uplift. The gradational relationship of the Hensel clastics and Glen Rose carbonates and the marine transgressive nature of the upper Trinity sequence are illustrated in figures 9 and 11 (in pocket).

It may be noted that the Hensel Sand, named after the homestead established in 1857 by Herman Ludwig Hensel on ranch lands adjacent to the old Marble Falls-Austin road crossing of Cow Creek, western Travis County (Locality Map D, Appendix), was misprinted as Hensell [sic] when formally introduced (Hill, 1901, pp. 142, 143, 145) despite earlier correct references to "Mr. Hensel's house, at Travis Peak post office" (Hill, 1890b, p. 120; Hill and Vaughan, 1898, p. 222, and 1902 [but dated 1900], p. 3). The two-story native stone house, the site of Travis Peak post office from 1870–1934 and a historic landmark continuously occupied by descendants and heirs of the pioneer Hensel

Disconformity	Geologic Characteristics			
	GENETIC SUCCESSION OF BEDS	BED RELATIONSHIP	TOPOGRAPHIC CHARACTER	ORGANIC CRITERIA
HENSEL ~~~~~ COW CREEK	Nonmarine ~~~~~ Marine	Marine offlap	Hummocky surface with relief of a few feet locally	None present
HAMMETT ~~~~~ SYCAMORE	Marine ~~~~~ Predominantly nonmarine	Marine onlap	Irregular surface with relief of a few inches locally	Bored surface Bored boulders Incrusting oysters

FIG. 8. Comparison of lower and middle Trinity disconformities.

to the present day, is adjacent to the family cemetery correctly named on the new (1966) 7.5-minute Travis Peak, Texas topographic quadrangle map. Reiterating the corrected spelling made earlier (Lozo and Stricklin, 1956, p. 70), the impropriety of retaining the name Hensell [sic] in the geologic nomenclature—by the implied legality of the Stratigraphic Code, Article 12 (Amer. Comm. Strat. Nomencl., 1961)—is clearly contrary to the facts of what is historically fitting and orthographically proper.

Lithologic Character

Hensel Sand (lower Glen Rose equivalent).—The oldest Hensel (fig. 9, in pocket) is comprised of continental and marine deposits which are described as follows.

The continental deposits, which are restricted to an updip position and exposed only in the Colorado-Pedernales drainage area, commonly contain a basal limy layer (Pl. VI, A) of probable secondary origin, variable amounts of red, green, and maroon clay in a succeeding position, and an upper sandy section with coarse channel gravels at the base (figs. 6 and 9). Both the clay and the sand appear to be part of an alluvial fan built out from the Llano region by streams flowing onto a low-lying coastal plain. The origin of the limy layer present in the more downdip localities, however, is not as obvious. It is irregular and nonstratified, composed of nodular, fine-grained limestone and dolomite, and contains abundant vertically oriented pockets and cracks filled with oxidized clay (Pl. VI, B). The clay likely fills a network of irregular crevasses produced by downward-percolating ground waters. These characteristics bear some similarity to calcareous soils forming in certain coastal regions of low rainfall, as in South Texas where a caliche mantle of the Lissie Formation is ascribed by Price (1958, p. 47) to the leaching and concentration of carbonates by evaporation of surface and soil waters. The basal limy deposits of the Hensel are in the proper sequential position to have been exposed to weathering and soil-forming processes, since they cover an abandoned beach and lie at the base of an alluvial fan.

The marine deposits of the Hensel are about 30 feet thick and consist primarily of sandy dolomite beds (fig. 9). They progressively replace younger continental beds updip and thus indicate a shift of the sea, accompanied by uninterrupted deposition, across an alluvial slope. The oldest dolomite beds that constitute the southernmost downdip Hensel (Section 3, fig. 9) contain appreciable clay, numerous siliceous concretions, and exceptionally large oysters. These beds, best exposed around the settlement of Spring Branch, Comal County, have been described in detail by Cooper (1964). Scattered *Orbitolina texana* and *Monopleura*-like rudists are common in the younger updip dolomite beds.

Lower Glen Rose member.—The lower Glen Rose is divided into two informal stratigraphic units on the basis of contrasting lithology (fig. 9). The lower unit (Unit 1) consists mostly of massive ledge-forming limestone beds comprised of shell fragments in a lime mudstone or sparry calcite matrix and has few interbeds of clay. It is subject to much variation in thickness, primarily through updip facies change to Hensel dolomite, and is popularly known from sporadic rudist and coral reef deposits and the local development of caves, such as Cascade Caverns and Century Caverns (formerly referred to as Cave Without a Name), Kendall County. Individual beds of this unit, although they may be laterally persistent, are extremely difficult to trace from one locality to another. Unit 2, in contrast, usually contains fissile dolomitic shale and dolomite beds in the lower part and alternating beds of clay and limestone in the upper part. These fine-grained limestone beds are traceable over a broad area and contain a variety of sedimentary features, some of which are indicative of intertidal deposition (Stricklin and Amsbury, 1969) and are the subject of later discussion. Unit 2 is of comparatively uniform thickness.

Many lower Glen Rose beds are very fossiliferous, with the most plentiful types being internal casts of pelecypods and gastropods deformed by compaction accompanying burial. Some of the typical fossils (Pls. VII and VIII) include a wide variety of mollusks, several kinds of echinoids, at least three different species of rudists, the dasycladacian alga *Porocystis*, and the disc-shaped foraminifer *Orbitolina texana*. A particularly varied fauna occurs in nodular limestone and clay at the top of Unit 2; these highly fossiliferous beds have been designated by Whitney (1952, p. 66) as the *Salenia texana* zone, after the occurrence of the distinctive regular echinoid (Pl. VII, g and h) by that name.

A thin accumulation of *Corbula martinae* (Pl. XIV, B) at the top of the lower Glen Rose is the most persistent and distinctive bed in the entire formation. This bed forms an iron-stained ledge that is easily recognized between the underlying white-to-cream-colored "*Salenia* marl" and an overlying porous zone of brown-to-red rocks stained by circulating ground waters. The "*Corbula* bed" is seldom more than 1 foot thick, is traceable over an outcrop area of at least 5,000 square miles, and is easily picked as a resistive point on many electric logs of water wells run in conjunction with the field work. For these reasons, the "*Corbula* bed" is a convenient horizon for structural and geologic mapping and is designated herein as the boundary of the upper and lower Glen Rose rather than the horizon of prominent lithologic contrast at the top of the bioclastic limestone of Unit 1.

Reefs are a subordinate lithology of the lower Glen Rose but one of the most interesting. A large reef containing abundant corals is developed in the basal part of Unit 1 a few miles southeast of Blanco, Blanco County, and the upper part of the unit is characterized over much of the investigated area by sporadic occurrences of rudist reefs. The reefs and other lower Glen Rose deposits of special environmental significance are discussed in a later section of the report.

Upper Glen Rose member.—In contrast to most of the lower Glen Rose, the upper Glen Rose is primarily a sequence of alternating resistant and nonresistant beds. The latter are comprised primarily of calcareous clay, and the resistant beds include dolomite, lime mudstone, and a variety of bioclastic, fine-to-medium-grained limestones. In addition, two evaporitic intervals from which gypsum is being leached in the present-day vadose zone are expressed at the surface by rubbly solution zones. Bed continuity and "stairstep" topography developed on resistant and nonresistant alternating beds are the dominant traits of the upper Glen Rose. These characteristics are readily apparent in the vicinity of Shingle Hill, Travis County, and Twin Sister Peaks, Kendall County.

Two stratigraphic sections are included to illustrate the details of upper Glen Rose stratigraphy. A depositional strike section (fig. 10, in pocket) shows a high degree of lateral continuity; whereas a depositional dip section (fig. 11, in pocket) shows progressive updip disappearance of beds through facies change and onlap over pre-Cretaceous rocks.

Eight distinct stratigraphic units are recognized within the upper Glen Rose section (fig. 10). From bottom to top, these units are as follows: Unit 1, a collapsed brown-to-red-stained breccia zone from which gypsum has been removed; Unit 2, thinly bedded, slightly fossiliferous clay, claystone, and limestone; Unit 3, nodular, very fossiliferous limestone and clay containing *Orbitolina texana* and abundant steinkerns of various species of gastropods and pelecypods; Unit 4, a sequence comprised mostly of calcarenite; Unit 5, a second collapse breccia zone resulting from leached evaporites; Unit 6, a clay section with thin, resistant beds of calcarenite and a few dolomite stringers; Unit 7, alternating beds of fossiliferous limestone, dolomite, and clay; and Unit 8, a terminal sequence of interbedded clay and finely crystalline dolomite. All eight units persist for at least 125 miles along the northeast-southwest dimension of the outcrop area. Some individual beds, a few of which are shown as markers in figures 10 and 11, have comparable distribution and are very helpful in tracing and correlating outcrops. The zonal occurrence of *Orbitolina texana* in Unit 3, which is the uppermost occurrence of this large foraminifer in the outcrop Glen Rose, is particularly helpful in stratigraphic orientation, as this resistant fossil is easily detected in "float" below this level.

All of the eight upper Glen Rose units progressively disappear updip within a distance of less than 25 miles (fig. 11)). All but the uppermost unit, which onlaps weathered caliche of unknown age, appear to grade transitionally into the underlying Hensel Sand. Within the transitional zone are isolated occurrences of uniformly cross-bedded coquina judged to be local beach accretions. An outcrop of this coquina, about 10 feet thick and with beds dipping 8 to 10 degrees, may be seen in the channel of Grape Creek at the town of Luckenbach, Gillespie County.

Hensel Sand (upper Glen Rose equivalent).—The younger Hensel is comprised of redbeds (Gillespie Formation of Hill and Vaughan, 1898) which grade from alluvial to near-shore marine sand and clay, both upward from the base and laterally downdip. These Gillespie County redbeds are considered to be equivalent in age to adjacent marine deposits of the upper Glen Rose. The approximate overall slope of the Paleozoic land surface on which these basal Cretaceous sands were deposited can be determined by extrapolating the Paleozoic unconformity (fig. 11) to a point 340 feet below the base of the Cypress Creek Section, based on subsurface data from a water well in that vicinity. The resultant slope is calculated to be about 700 feet in 24 miles, or slightly less than 30 feet per mile. This is more than, but probably close to the original depositional slope (since there is only slight downdip thickening of Trinity deposits as a result of tilting during sedimentation) and is of sufficient magnitude to suggest that the streams which transported the sand and clay did not become aggradational until they nearly reached the coast. If so, deposition of the redbeds is genetically related to marine transgression, and the redbeds are only slightly older than the overlying upper Glen Rose deposits.

The youngest Hensel thins updip by onlap (fig. 11). Along its feather edge, it rests on a nodular limy layer which is similar to the caliche present at a lower stratigraphic position above the Cow Creek Limestone. This limy accumulation may also be a fossil caliche, but its age could range from Paleozoic to Lower Cretaceous since it overlies Paleozoic rocks. The updip thinning and local absence of the basal Cretaceous sand and its replacement by marine deposits indicate that the Llano Uplift was an insignificant sediment contributor by the close of Trinity time.

INTERVALS OF MAJOR ENVIRONMENTAL SIGNIFICANCE

The most significant intervals of the Glen Rose, from an environmental point of view, are those that include reefs, intertidal deposits, the "*Corbula* bed," and collapse breccia zones resulting from leached evaporites. These environments, as interpreted by several lines of evidence including a wide variety of sedimentary features, are treated separately in the following discussion.

Reef Beds

Numerous local reef deposits occur within Unit 1 of the lower Glen Rose within the area shown in figure 12. The majority are fairly small mounds developed in the upper part of Unit 1, but several more extensive tabular reefs are present at the same stratigraphic position, and an older one occurs within the lower 100 feet of the unit.

The small mounds (Pl. IX, A) appear to be analogous to patch reefs developed in lagoons of present-day reef tracts. They

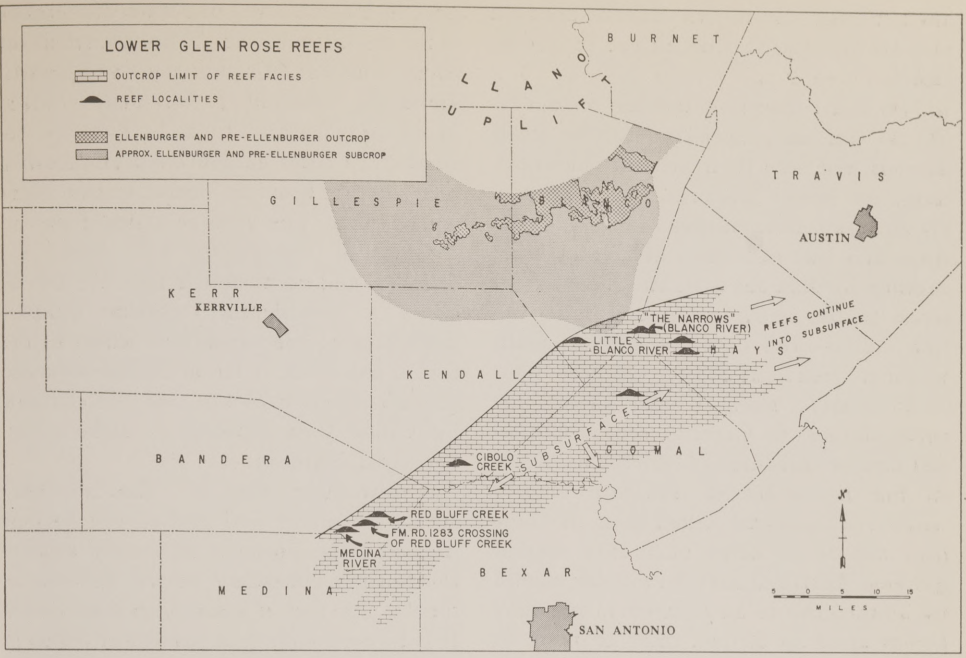

FIG. 12. Regional map showing localities of lower Glen Rose reefs.

are circular to slightly elongate in plan view, are usually less than 75 feet across and no more than 30 feet thick, have flat or slightly down-bulging bases, and are composed primarily of both steinkerns and shells of caprinid-type rudists in a lime-mudstone matrix. Many of the rudists are unbroken, closely crowded together, and appear to be in erect growth positions; hence these gregarious pelecypods, with a growth habit similar to corals, probably created a baffle for lime mud accumulations on mounds that projected slightly above the surrounding sea bottom. Bedding is obscure within the mounds, but they are generally overlain by beds which dip radially away at angles of up to several degrees. Whether these beds grade into reef material by facies change or abut against the flanks of the mounds as later deposits is not clear-cut. Both relationships probably exist, with the uppermost intermound beds abutting discordantly against the reefs. These reefs and their associated facies have been the subject of detailed investigations by Perkins (1968, 1970). For additional information on these lower Glen Rose reefs, the reader is advised to watch for the following papers by Perkins, which are in various stages of preparation for publication as indicated: "Geology of a Rudist Reef Complex," Journal of Paleontology; "Cretaceous Reefs in Western Gulf of Mexico," Proceedings of First North American Paleontologic Conference; and "Genetic Implications of Rudist Reef Architecture," Society of Economic Paleontologists and Mineralogists Special Paper.

Mounds such as those described above are best developed in southern Bandera County (fig. 12). They are ideally exposed at low positions in stream banks along a one-half mile stretch of Red Bluff Creek, about 2 miles downstream at the crossing of Farm Road 1283 over Red Bluff Creek, and along the west bank of Medina River within the upper reaches of Medina Lake. Numerous mounds also exist along drainage ways of the Guadalupe and Blanco Rivers in northern Comal and western Hays counties, but these mounds are generally difficult to observe because of their high position on hills or in stream bluffs.

The more extensive tabular reefs (Pl. IX, B) are less numerous than the small mounds and only their general characteristics are known because their size precludes complete exposures in any one outcrop. The best exposures of tabular reefs developed within the same stratigraphic interval as the small mounds occur in the bed of Red Bluff Creek, 1½ miles south of Pipe Creek community, southern Bandera County; along Cibolo Creek just north of Cascade Caverns, southern Kendall County; and along Little Blanco River on the Davis Ranch, southern Blanco County. The lateral dimensions of these reefs are on the order of at least several hundred feet (and may be greater should the reefs prove to be elongate), and they are as much as 50 feet thick or more in central parts. As in the small mounds, caprinid-type rudists (Pl. X) are the dominant faunal component, but corals and coralline algae also occur as minor elements. In contrast to the mounds, the tabular reefs appear to contain more abundant original shells and shell fragments in a matrix which varies from lime mudstone to sparry calcite. The latter, which infills primary void space, is probably indicative of a higher degree of wave action related to seaward geographic position or topographic prominence above the mounds. A more direct indication of vigorous wave action is provided by a 15-foot sequence of fringing reef talus beds which dip away from the southern front of the Red Bluff reef at angles of up to 7 degrees. The thickness of this reworked talus, cemented by sparry calcite, establishes a minimum water depth of 15 feet.

Another large tabular reef has been described previously (Lozo and Stricklin, 1956, p. 70), along "The Narrows," a scenic gorge of the Blanco River in westernmost Hays County. In contrast to the tabular reefs described above, "The Narrows" reef occurs within the basal 100 feet of the lower Glen Rose and is composed predominantly of corals. *Montastrea* is the most spectacular if not the principal coral, with heads ranging up to 3 feet in diameter; however, J. W. Wells (1932), based on collections by F. L. Whitney, described 29 coral genera from this locality and younger mounds located several miles downstream. The reef is exposed over a distance of one-quarter mile along the channel, and coral debris may be seen in bluffs a considerably greater distance downstream; the subsurface extent of the reef is unknown. A 10- to 15-foot sequence of shell debris caps the reef and contains individual beds dipping at angles of up to several degrees.

A few miles west of "The Narrows" coral reef, water well and oil test borings indicated the presence of locally shallow Ellenburger limestone buried beneath as little as 200 feet of lower Glen Rose strata. It is thus possible that growth of corals in this area may have been favored by an island of Ellenburger limestone, which served as a barrier preventing marine influx of land-derived detritus.

Intertidal and Shallow-Water Features

Sedimentary features of intertidal origin occur throughout Bandera, Kendall, and southern Blanco counties in a thin, 6-foot interval of the lower Glen Rose (Unit 2), about 40 feet above the horizon of rudist reefs. These include laminated algal and rippled beds developed over an extensive area and other features of local importance.

The top of this interval is defined by a thin, laminated algal bed, which has been mapped over an area of several hundred square miles, and a similar but less extensive bed is present at the base. Both beds are composed of thin, dark laminae interstratified with lighter bands of fine-grained calcarenite and are characterized by small, apparently accretionary mounds known as stromatolites (Pls. XI; XII, B). The origin of these beds is attributed to mat-forming, blue-green, filamentous algae.

The mode of accumulation of this type of algal sediment is well known from a study by Black (1933). He reported that blue-green, filamentous algae locally cause the accumulation of laminated sediments on Andros Island, within and just above the intertidal belt (p. 169), and that these laminated sediments are formed by the repetition of two processes—the development of mucilaginous algal mats on moist surfaces or on the bottom of shallow ponds and the entrapment of sediment grains as they are transported across the sticky surfaces during tidal sweep or rainy periods (pp. 176–177). Because no hard parts of this type of alga are preserved, the assignment of an algal origin to the Glen Rose beds is based primarily on their physical resemblance to present-day algal deposits. In addition to the striking resemblance between the stromatolites and modern algal heads (Pl. XI, A), another criterion for identifying this type of algal sediment is evidence of the influence of an adhesive film seen in calcarenite layers deposited on steeply inclined, vertical, or overhanging surfaces (Ginsburg, 1955); as displayed on the crenulated left side of the largest stromatolite in Plate XI, B, such unusual depositional attitudes are due to the stickiness of the algae. Stromatolites of both beds in Unit 2 locally display such evidence.

Each algal bed is commonly underlain by a thin calcarenite bed with one or more layers of well-defined ripple marks. In areas of multiple ripple marks, the individual 2- to 3-inch flagstone layers are characterized by excellent bedding cleavage and are exploited as building stone, particularly around the town of Comfort, Kendall County. The ripple marks are symmetrical and may be classified into two types. Their crests are low in relief, broadly rounded, and 2 to 4 inches apart; in plan view, they either are parallel, thereby fitting the description of oscillation ripple marks, or form interlocking patterns typical of interference ripple marks. The orientation of the ripples has been measured at numerous localities and is dominantly northwest-southeast for more than 100 miles along the outcrop. These properties suggest that the ripples formed in standing water agitated by the wind with the dimpled interference patterns probably resulting from abrupt wind shifts which superimposed one ripple set on a previously formed set. The water in which the ripples formed must have been shallow, as indicated by the associated algal beds. Considering their effectiveness as sediment binders, the algae responsible for these beds probably accounted largely for preservation of the underlying ripple marks.

In addition to stromatolitic beds and rippled surfaces, the rocks in this interval also contain bored surfaces and mudcracks (Pl. XIII), dinosaur tracks, oyster shells incrusted onto bedding surfaces, and rippled bar deposits (Pl. XII, A). Some of these features, like the algal beds, point to exposure of the sea bottom. The mudcracks are indicative of dessication, and the associated clam borings and oyster-incrusted surfaces provide supplementary evidence of marine substrates hardened through drying. Dinosaur tracks, which are in some cases developed on bored and mudcracked surfaces, as at La Jita Girl Scout Camp, Utopia, Uvalde County, are probably preserved because the animals walked or waded across a partially hardened crust. It seems highly probable that these features formed in an intertidal zone from which shallow water occasionally withdrew, or was driven off by strong winds, to allow at least partial drying of sea floor sediments.

Corbula Bed

The mid-Glen Rose "*Corbula* bed," named from the abundant occurrence of the small clam *Corbula martinae* (Pl. XIII, B), is the basal bed of a sequence in which variable thicknesses of gypsum occur in the subsurface. The fact that *Corbulas* occur not only beneath the evaporite sections but also in local stringers between the gypsum beds indicates that these clams had a high tolerance for hypersaline waters. Based on the assumption that salinity was critically controlled by water circulation, the "*Corbula* bed" indicates a pronounced change in circulatory conditions from those of a freely circulated body of water, represented by the underlying profusely fossiliferous, nodular limestone (*Salenia texana* zone), to those of a restricted water body, in which the overlying evaporites accumulated. The *Corbula* stringers between the evaporites probably reflect minor improvement in water circulation and reduction in salinity.

Two distinct modes of *Corbula* occurrence indicate sediment reworking by currents or waves over much of the outcrop area. In the eastern half of the area, the "*Corbula* bed" is composed almost totally of *Corbulas* and usually contains broad, irregularly trending ripples (Pl. XIV, A); whereas, in the western part of the area the bed is thicker, seldom rippled, and composed primarily of fine-grained material containing only scattered *Corbulas*. Because *Corbula* is a burrowing clam, the latter facies represents the burial of undisturbed sediment. In contrast, the other facies implies that fine-grained sediment was removed from the eastern part of the shelf by winnowing action, leaving behind a reworked concentration of *Corbula* shells. The associated ripple marks are also in keeping with this conclusion. The irregularity of the ripple trends and the asymmetrical ripple form imply that currents, rather than waves, were the reworking agent.

Evaporites

The beds of Units 1 and 5 of the upper Glen Rose are largely of evaporitic origin, although evaporites are never seen at the surface. Because of similarity in their appearance and origin, only Unit 1, the interval immediately above the *Corbula* bed, is considered here.

Gypsum, as identified by X-ray analysis, is the major subsurface constituent of the interval (Unit 1) throughout the western part of the investigated area and occurs as two beds with a combined thickness of no more than 15 feet (fig. 13). The entire interval reaches a maximum subsurface thickness of 25 feet in Bandera County. If the interval is above the zone of permanent water saturation, as is the case at the outcrop, the gypsum beds have been leached by downward-percolating ground waters, resulting in an incomplete, collapsed section (fig. 13). The removal of evaporites has caused uneven settling of claystone beds formerly between or overlying the gypsum and the attendant development of extension joints and fractures in these dislocated rocks. Because initial permeabilities have been enhanced by such jointing and fracturing, the interval is an excellent aquifer and contributes much of the local water supply. Where these rocks crop out in valleys, seeps and springs are common, and some discharge large volumes of water during rainy seasons.

The outcrop of this interval is prominent because of the buff-orange color of two layers of recrystallized claystone and dolomite that originally were adjacent to or intercalated with the gypsum beds. The color probably results from oxidation of minor amounts of iron-bearing minerals. Other features within the interval include small faults (Pl. XV, A), contorted beds, cemented or infilled joints, and bedding planes which weather differentially to produce striking "boxwork patterns" (Pl. XV, B). All of these features are a result of processes related to subaerial erosion of the present-day terrane and may serve as criteria in identifying ancient solution zones and associated erosional unconformities.

Deposits downdip or seaward of the gypsum beds are outside the area of investigation; consequently, no equivalent restrictive barriers are known to account for evaporite deposition. The necessary restriction of water circulation may have been provided by shallow depth. Since shallow waters prevailed in the investigated area during much of Glen Rose time,

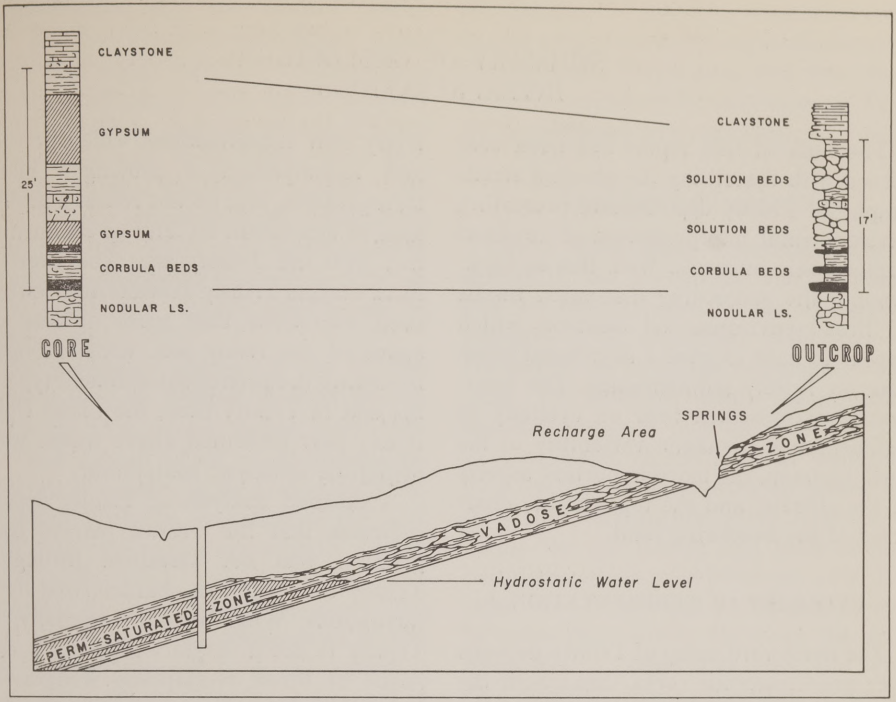

Fig. 13. Surface and subsurface relations of evaporite aquifer.

the evaporites may be precipitates resulting largely from excessive evaporation during periods of extreme aridity.

Trinity-Fredericksburg Boundary

The relationship between terminal Glen Rose clay and dolomite and basal Fredericksburg nodular limestone is one of probable disconformity over much of the investigated area. Evidence for this relationship consists of numerous locally-bored surfaces on uppermost Glen Rose beds and eastward thinning of the Glen Rose clay and dolomite section (Unit 8, fig. 10), as opposed to fairly uniform thickness of older Glen Rose units. This thinning is attributed to progressive eastward removal of older beds by subaerial erosion toward the more positive San Marcos Arch located in Blanco, Hays, and Travis counties.

The interpretation of a disconformity developed on terminal Glen Rose deposits is in agreement with conclusions presented by Moore (1964) and Lozo and Smith (1964) from later investigations. Moore (pp. 6, 11) reported that Fredericksburg limestone unconformably onlaps Glen Rose deposits in Hays, Blanco, and Travis counties, and that farther northward in Williamson and Burnet counties the upper Glen Rose surface is marked by pholad borings, mudcracks, dinosaur tracks, and local occurrences of reworked bored pebbles and boulders in overlying beds. Westward in Real and Edwards counties, Lozo and Smith (pp. 291, 293) reported that basal Fredericksburg nodular limestone rests disconformably on bored, oyster-incrusted, weathered dolomite of the upper Glen Rose.

SUMMARY OF GEOLOGIC INTERPRETATIONS

The bulk of this report has been concerned with describing the physical stratigraphy of Trinity deposits and presenting environmental interpretations of confined stratigraphic intervals. With this as background, the succeeding discussion dwells on broad environmental elements which appear to have exerted a significant influence on Trinity sedimentation. The interpretations presented bear on cyclicity of sedimentation, dynamic variability of the shelf regimen, the more important aspects of the climate, and the topographic character of the bordering land.

CYCLICITY OF SEDIMENTATION

The northward onlap of Trinity deposits over pre-Cretaceous rocks throughout the outcrop area indicates prolonged sea encroachment of the Llano Uplift during Trinity time. Within the massive wedge of Trinity deposits, the basal sands (Sycamore and Hensel) are initial, comparatively thin accumulations which preceded and accompanied a prolonged marine transgression, and do not reflect a high degree of deposition on land or sediment influx into the Trinity sea. The overlying thick marine Trinity deposits are viewed as shelf accretions that more or less kept apace of the rising sea, with carbonates becoming the prominent sediment type. By the end of Trinity time, the Llano Uplift, if any part remained above water, was a negligible sediment contributor.

A detailed analysis of Trinity deposits indicates that the overall marine transgression was not sustained throughout Trinity time but was characterized by interruptions. When viewed internally, the Trinity is not a single wedge but a composite of three overlapping wedges—the lower, middle, and upper Trinity (fig. 14). Each wedge is characterized by basal terrigenous clastics followed by marine carbonates, and the deposits of each wedge are terminated by a disconformity. These

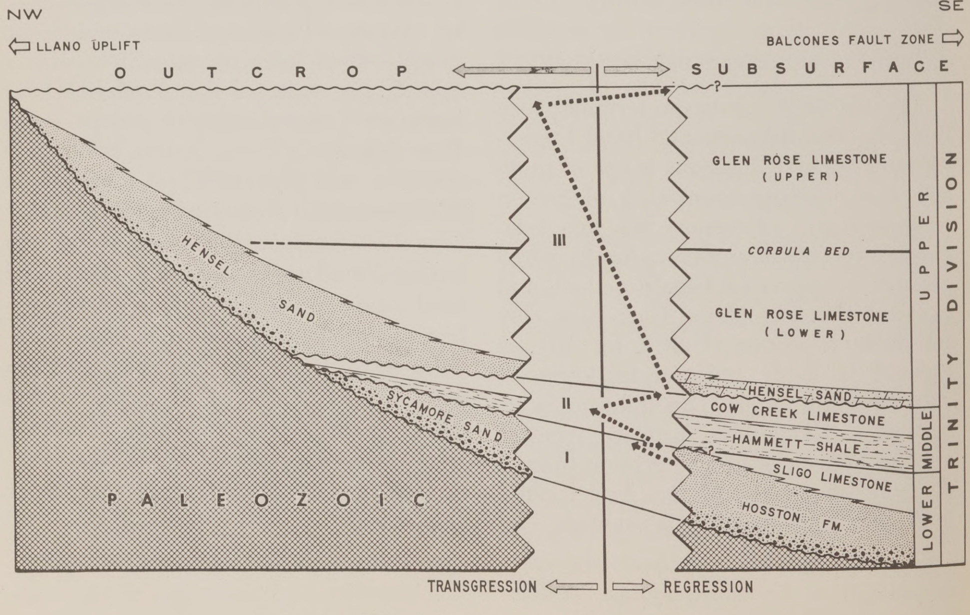

FIG. 14. Cyclical diagram of the Trinity Division.

disconformities, plus the upward gradation of terrigenous-to-carbonate rocks within each wedge—and the resulting contrast in contiguous rock types between wedges—indicate that the overall Trinity transgression was cyclic rather than continuous and that the lower, middle, and upper Trinity represent three depositional cycles (fig. 14). Each cycle corresponds to a marine transgression that was terminated by regression or relative equilibrium of land and sea.

The regressive phases of the Trinity cycles have only limited vertical expression in the rock record; hence, their duration and overall effect on sedimentation were minor relative to the preceding transgressions. With the exception of the middle Trinity, the cycles are actually depositional half cycles and are graphically illustrated by pronounced asymmetry (fig. 14). Areally, the most pronounced regression is that inferred from the extensive seaward growth of Cow Creek beaches at the close of middle Trinity time. The resulting enlargement of the land area through this beach growth accounts for the seaward-extending tongue of Hensel Sand between regressive carbonates of the underlying Cow Creek and transgressive carbonates of the overlying Glen Rose. Regressive phases of the other cycles are inferred by terminal disconformities, but no other significant regressive deposits are preserved within the Trinity.

VARIABILITY OF SHELF REGIMEN

The lateral continuity of individual marine beds and facies within the outcrop Trinity suggests uniformity of deposition on a broad shelf with gentle seaward slope. However, significant vertical variations in rock types, sedimentary features, and type and abundance of fossils indicate changeability of water circulation over the shelf. Water depth, which largely determines the magnitude of wave and current action on modern shelves, can be demonstrated for some Trinity deposits and is postulated as the dominant factor in controlling water circulation. The following discussion is intended to summarize views on extremes of Trinity water circulation and provide a frame of reference for the range of Trinity depositional environments.

Low-Energy Deposits

Lower Glen Rose intertidal deposits exemplify the low-energy shelf regimen and are characterized by the widespread persistence of individual beds and an abundance of revealing sedimentary features. The evidence within the intertidal sequence suggests that the indicated low level of water circulation was controlled by very shallow water over an almost flat shelf. In this setting blue-green algae spread across the sea bottom and built stromatolitic accretions over hundreds of square miles, low relief ripples probably formed by prevailing winds disturbed the sediments over a comparable area, and large land-dwelling dinosaurs walked or waded scores of miles from the average Trinity shoreline. Intermittently, the shallow waters apparently retreated from the shelf, possibly during low tides or periods of persistent offshore winds, and sediments were exposed, at least briefly, to become semiconsolidated or lithified under atmospheric conditions. The evidence for this includes mudcracks, oyster shells incrusted onto bedding planes, surfaces bored by clams that required a firm substrate for habitation, and rims around dinosaur tracks indicating sediments were in a cohesive, plastic state when the tracks were formed. In numerous localities, combinations of these features occur on the same bedding surface. Within the low dynamic threshold represented by the intertidal zone, the net result of shallow-water sedimentation interrupted by repeated sea floor exposure has been stratigraphic continuity of distinctive beds that certainly rank among the most interesting and revealing within the Trinity.

After deposition of the intertidal beds, water circulation on the Trinity shelf improved vastly as indicated by the profuse fauna in the overlying 10- to 20-foot sequence of nodular limestone (*Salenia texana* zone). However, this efficient circulation did not persist during accumulation of the succeeding deposits. The overlying mid-Glen Rose evaporites—and the similar section 200 feet higher in the same formation—are considered to be additional examples of deposits resulting from a low-energy shelf regimen. The evaporites themselves are first-hand evidence of restricted water circulation, regardless of whether the condition was brought about by isolation of deeper waters behind barriers or excessive evaporation of shallow waters during extreme aridity. Unlike the intertidal zone, however, individual beds of the evaporite intervals are virtually impossible to trace for any distance on the surface due to subsurface removal of the evaporites and the resulting collapse and alteration of intervening and overlying beds. A few cores obtained from the unaltered mid-Glen Rose evaporite section suggest that diagenesis is responsible for obscuring continuity of bedding. Otherwise, individual beds of both evaporite intervals would possibly be traceable over broad areas, like the *Corbula* bed which persists at the base of the lower interval for thousands of square miles.

High-Energy Deposits

Cow Creek beach deposits of the middle Trinity provide a notable record of the high-energy shelf regimen. Events prior to deposition of the underlying Hammett Shale, that is, steepening of the shelf slope by tectonism (or erosional steepening of the land surface) and a relative rise in sea level, set the stage for middle Trinity deposition. Although the vertical sequence of Hammett Shale and Cow Creek Limestone reflects progressive shallowing, the steep shelf profile was apparently maintained during middle Trinity deposition, allowing strong currents to swing in close to shoreline and large waves to break against the mainland. Under these conditions, the three seaward-shifting facies of the Cow Creek developed, and the land area was extended significantly seaward by progradation of beach deposits.

Some beaches of the Gulf of Mexico and Atlantic Ocean are apparently being formed under conditions similar to those of the Cow Creek. Some parts of Galveston Island, for example, have grown seaward over a distance of 2 to 3 miles in the last several thousand years through the addition of terrigenous sediment swept in by currents and waves (LeBlanc and Hodgson, 1959, pp. 213, 215). Elsewhere, in the Bahama Islands area, numerous capes are being enlarged through the initial deposition of festoon cross-bedded carbonate sand, where currents are checked, and succeeding accretions of uniformly sloping beach beds added as a result of wave action (Ball, 1967, pp. 584–585). The resulting sequence of cross-bedding, as illustrated by Ball, is strikingly similar to that of the Cow Creek.

The average thickness of Cow Creek beach deposits, which represent upbuilding of the beach face to sea level, suggests that water depth a short distance in front of middle Trinity beaches was on the order of 20 feet. The Cow Creek beds deposited under such efficient circulatory conditions are characterized by local lenticularity, but individual facies are widespread. In contrast to some middle Glen Rose beds that extend over hundreds of square miles, individual beds of the Cow Creek beach sequence are traceable only over several hundred square feet or less.

Reefs of the lower Glen Rose are another example of high-energy deposits resulting from a high degree of water circulation. The evidence for this is a varied fauna containing large rudists and corals that depended on efficient water circulation for food supply, the abundance of coarse, abraded shell debris in the larger reefs, and shingle beach-like accretions fringing or overlying the larger reefs. With regard to the latter, coarse cobbles of worn, coral heads and rudists testify to the strength and ability of currents to scour and transport sediment, as does festooned cross-bedding that is present locally in the flanking reef accretions at Red Bluff Creek and "'The Narrows." Relative to the energy level of the environment, the matrix lime mud in the small mounds is misleading; however, it is compatible within this setting when viewed as accumulations in locally protected sites between rudists, which probably served as baffles to reduce currents. Some idea of water depth proximal to the seaward front of Trinity reefs is afforded by the 15-foot sequence of reef-flank accretions at Red Bluff Creek. Although it cannot be demonstrated that these accretions built up to sea level, with near uniform dips of approximately 7 degrees, the thickness of the sequence establishes a minimum water depth at this locality. Water depth of this magnitude and the resulting efficient circulation, as in the case of Cow Creek beaches, has led to an association of facies characterized by variability and discontinuity of individual beds.

CLIMATIC SETTING

The aspects of Trinity climate to be considered in the following discussion are those of humidity and temperature.

The several accumulations of paleo-caliche and gypsum in the Trinity are indicative of excessive evaporation. Although it is theoretically possible to have high annual evaporation in regions of abundant rainfall, it seems improbable that deposits as thick as these could have been formed during dry seasonal variations of a humid climate. The most reasonable interpretation is that of an arid-to-semi-arid climate. Since the gypsum and caliche deposits occur at several horizons in the Trinity, they probably indicate a prevalent climate of low rainfall punctuated by periods of excessive aridity. Contrary to this statement is the evidence of mild climate indicated by the occurrence of cycad fossils in the Hensel.

An insight into Trinity water temperatures is afforded at some stratigraphic levels by rudist and coral faunas and inferences drawn from their world-wide distribution. Reef-building rudists, as summarized by Palmer (1928, p. 18), lived abundantly in a belt lying mostly north of the present equator and extending from the western Himalayas—southern Europe region westward across the West Indies into northern Venezuela, Mexico, Texas, and Baja California. Modern colonial corals are reported to attain populous growth only in tropical and sub-tropical waters (Wells, 1956, p. 358). If modern colonial coral distributions are considered analogous to those associated with Lower Cretaceous rudist reefs, they would suggest that Trinity seas were warm, at least during times of reef growth. The subject of paleo-temperatures of Trinity sea water could be further pursued through oxygen-isotope analysis of calcitic shell fragments, but the question of variability of atmospheric temperature would still remain. Generally, mean air temperature would be expected to correlate with mean water temperature in shallow bodies of water not subject to rapid circulatory exchange and thermal depth gradients. In south Florida, for example, Lloyd (1964, pp. 86–87, and personal communication, 1967) reported that mean water temperature of Florida Bay and the open reef tract are approximately equal to the annual mean temperature of the atmosphere.

CHARACTER AND INFLUENCE OF LAND ON SEDIMENTATION

The Llano Uplift adjacent to the Trinity shelf apparently did not have the form of a low-lying coastal plain, as implied by the slope of the unconformity developed on Paleozoic rocks, the similar upper slope of the overlying sand mantle near its marine interface, and the hilly relief of the unconformity. The overall slope of the unconformity is as much as 30 feet per mile, relative to Trinity datums, with local relief of buried hills ranging up to 150 feet. Prior to burial, some of these hills must have been islands along the coast of the advancing sea. These characteristics indicate that the coastal terrane of the Trinity was quite irregular, with an average seaward slope several times greater than most of the present-day low-lying Gulf Coastal Plain.

All the foregoing factors formed a combination which did not favor extensive erosion of the continent. In contrast to the modern Gulf Coastal Plain and its prevailing depositional regimen, the streams draining the Llano Uplift during Trinity time were relatively insignificant as sediment contributors. They built no large deltas and were ineffectual in reducing the land to a typical alluvial coastal plain; if any drained a large continental interior, this is not evident from the bulk of their deposits. Chiefly because of the minor sediment contribution of streams, the Trinity shelf was largely a locale of marine sedimentation with carbonate deposits commonly extending to the shoreline. The reconstructed shore and near-shore depositional environments therefore appear to be intermediate between those of the present-day terrigenous sedimentary domain of the western Gulf Coast and the pure carbonate-type sedimentary province of southern Florida and the Bahamas, but depositional features are similar as a result of controlling hydrodynamic forces in each province. Within the Trinity depositional setting, restricted alluvial fans formed onshore, and variations in water depth and circulation over a broad shelf of gentle relief led to the development of contrasting morphologic features such as reefs, coquina beaches, and expansive carbonate tidal flats along a shore of relatively steep slope and hummocky relief.

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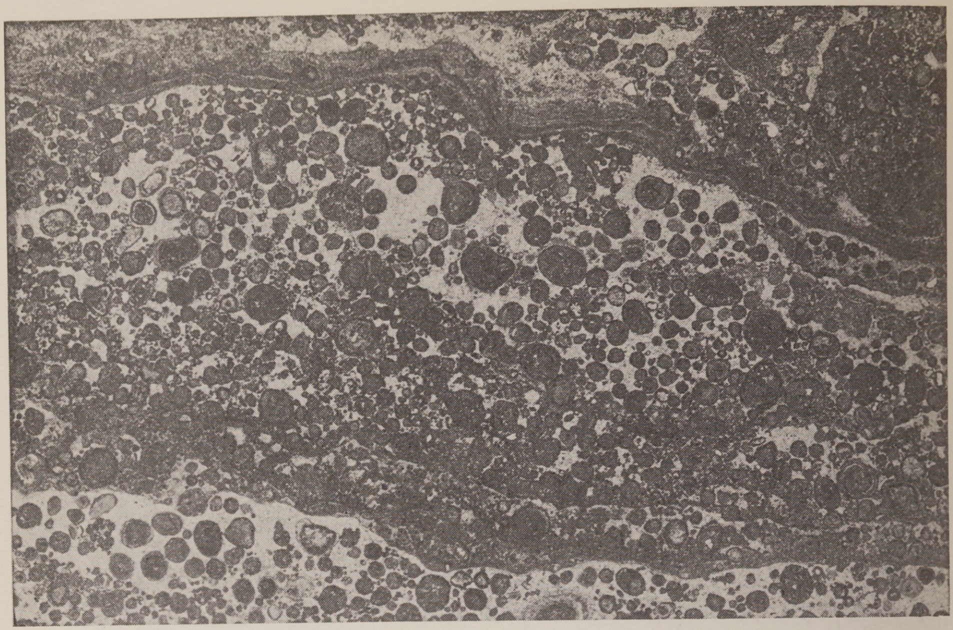
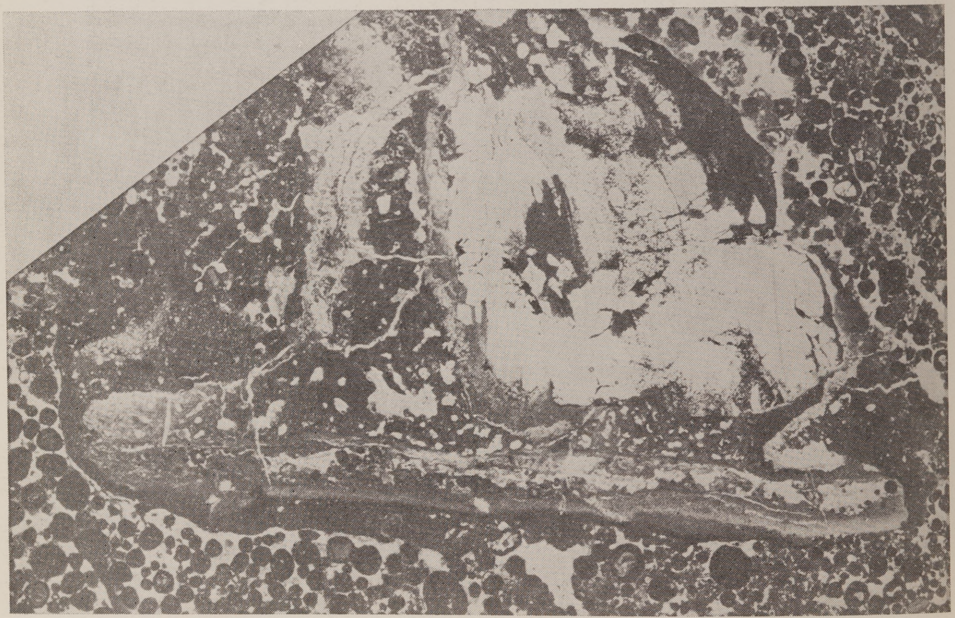
Plates I–XV

Lower Cretaceous Trinity Deposits, Central Texas **Plate I**



(A) Typical ooliths and irregular laminations, x4



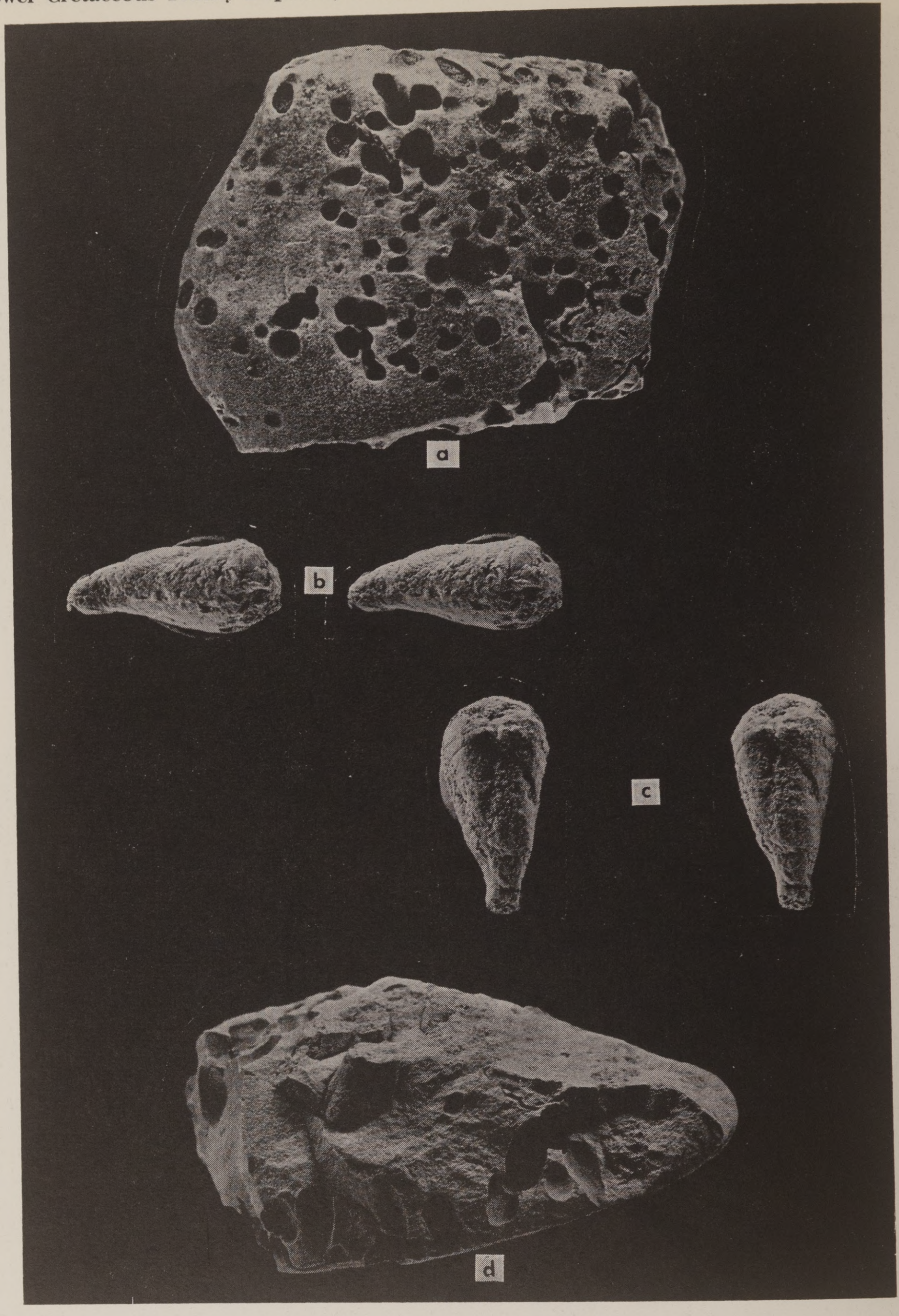
(B) Laminated pedestal structure developed beneath siliceous pebble, x4

Thin-section views of upper Sycamore caliche exposed on Lawson Ranch, approximately 4 miles southeast of Cypress Mill, Blanco County, Texas.

Lower Cretaceous Trinity Deposits, Central Texas

Plate II

Plan view of Sycamore conglomerate showing clam borings in beveled Paleozoic limestone and dolomite pebbles. This surface of disconformity, a result of marine transgression over Lower Trinity alluvial deposits, displays this character locally in exposures north of the Colorado River, Burnet County, where cemented conglomerates are in contact with Hammett Shale.



Typical reworked pebbles associated with Lower Trinity disconformity

Top view (a) and side view (d) of bored Ellenburger pebble showing section across borings and broken steinkerns of clams in growth attitude, x0.8. Stereoscopic views of boring pelecypods, right valve (b) and dorsal view (c), x1.5.

(A) Dip view of foreshore and backshore beds and intervening beach crest

(B) View down channel of Cow Creek showing offlapping sequence of dipping foreshore beds

Beach stratification in Cow Creek Limestone, in channel of Cow Creek, one-half mile east of road crossing to Hensel ranchhouse, Travis County, Texas.

Lower Cretaceous Trinity Deposits, Central Texas **Plate V**

(A) Irregular, subaerially eroded surface of disconformity overlain by continental deposits

(B) Calcareous mounds or possible dunes resting on foreshore beach beds.
Relief of mounds ranges up to 5 feet.

Features along upper Cow Creek disconformity in channel of Cow Creek, one-half mile east of road crossing to Hensel ranchhouse, Travis County, Texas.

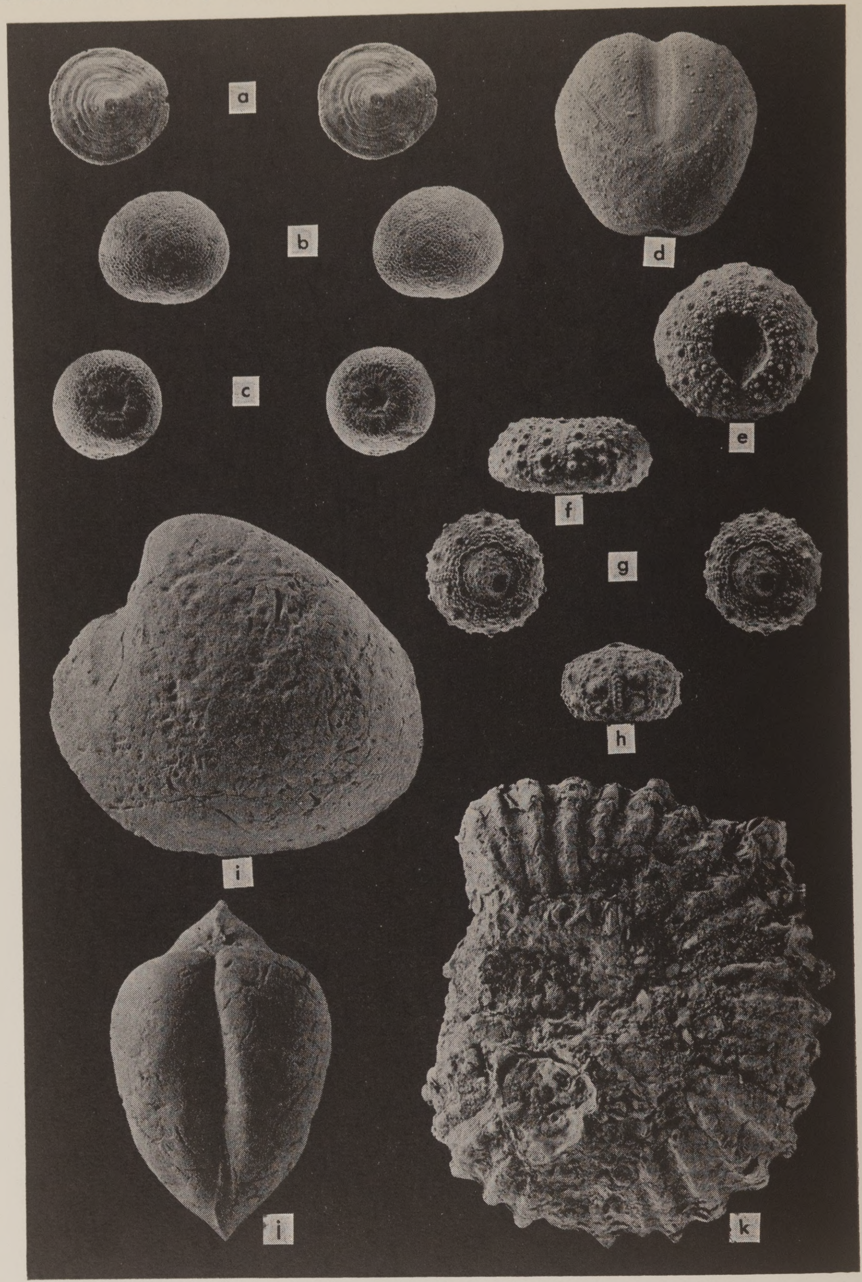
Lower Cretaceous Trinity Deposits, Central Texas **Plate VI**

(A) Bluff showing intermediate position of caliche in a beach-to-alluvium sequence

(B) Close-up view of nodular caliche showing vertical solution cracks filled with red and green clay

Continental deposits of Hensel Formation. Locality is on Cow Creek, one-half mile east of road crossing to Hensel ranchhouse, Travis County, Texas.

Lower Cretaceous Trinity Deposits, Central Texas **Plate VII**



Fossils from Glen Rose Formation

(a) *Orbitolina texana* (Roemer), top view (stereoscopic pair), x3; (b) and (c) *Porocystis globularis* (Giebel), basal and top views (stereoscopic pairs), x0.7; (d) *Enallaster obliquarus* Clarke, apical view, x1.5; (e) and (f) *Loriolia rosana* Cook, apical and side views, x1.5; (g) (steroscopic pair) and (h) *Salenia texana* Credner, apical and side views, x0.7; (i) and (j) *Meretrix hanseni* Whitney, left side and dorsal views of steinkern, x0.7; (k) *Douvilleiceras* sp., side view of steinkern, x0.7.

Lower Cretaceous Trinity Deposits, Central Texas **Plate VIII**

Fossils from Glen Rose Formation

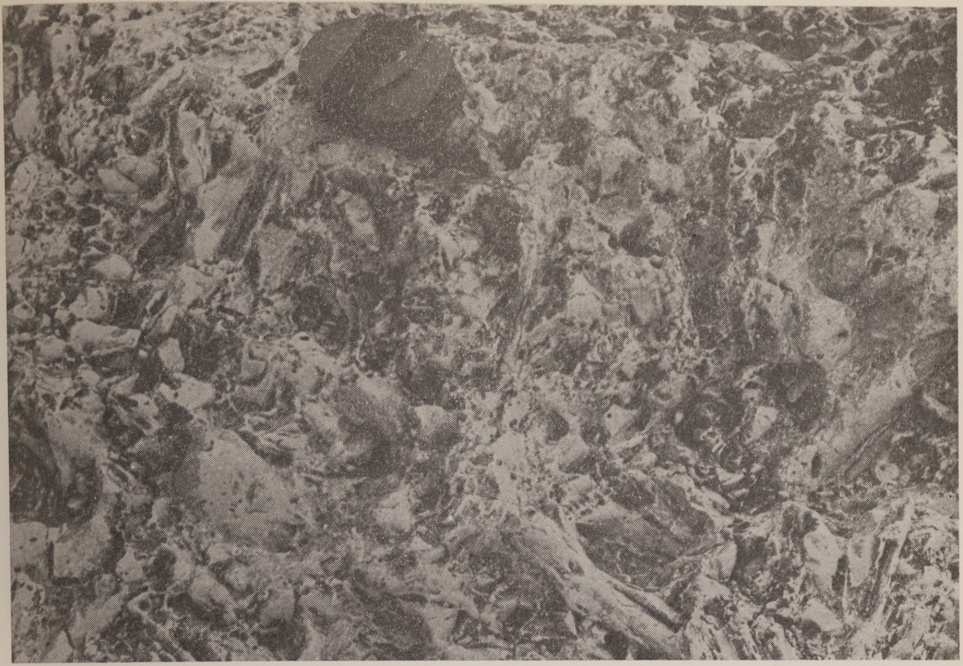
(l) *Lunaria ? pedernalis* (Roemer), apertural view of steinkern, x0.7; (m) caprinid, side view of right valve, x0.7; (n) *Knemiceras* sp., side view of skeinkern, x0.7; (o) and (p) *Toucasia* sp., side dorsal views of left valve, x0.7.

 Plate IX

(A) Small mound with concave base, enclosed by beds of lime mudstone

(B) Eroded edge of large tabular reef

Rudist reefs in lower member of Glen Rose Formation. Exposures are in channel of Red Bluff Creek, 1.5 miles south of the community of Pipe Creek, Bandera County, Texas.

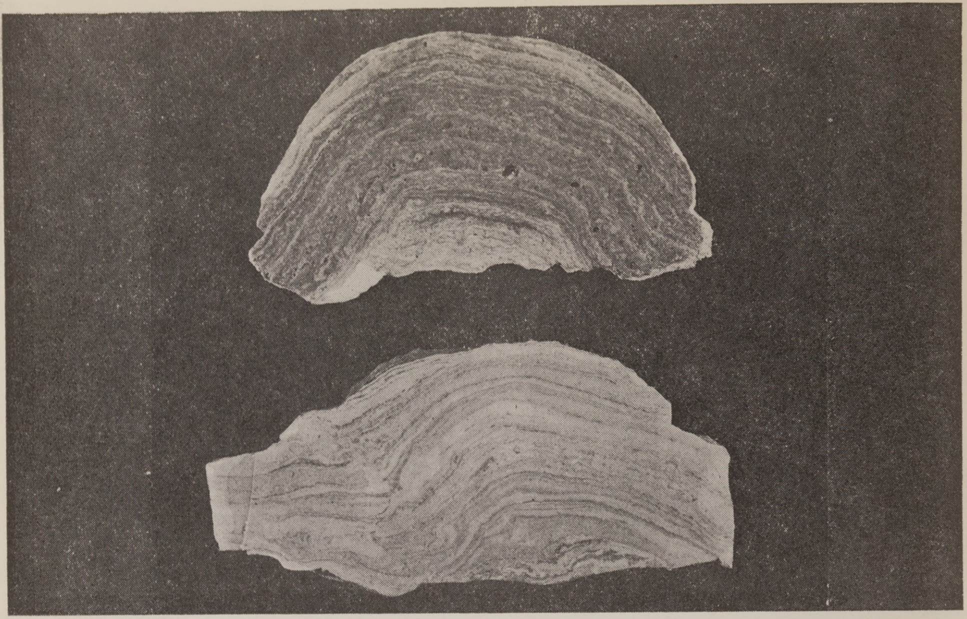


(A) Caprinid shells in growth position

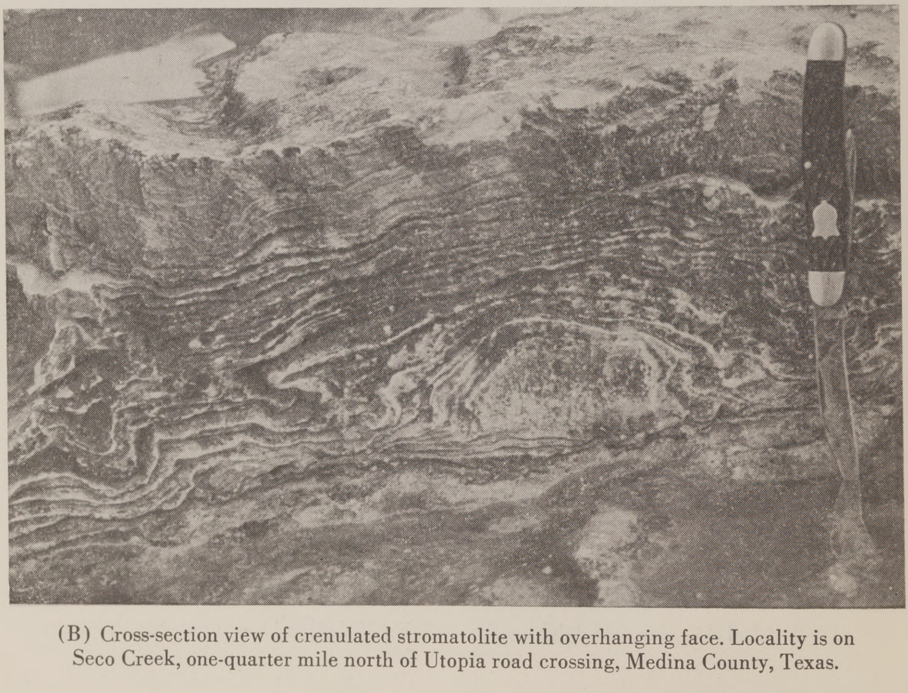
(B) Polished slab of caprinid debris. Cross section of shell in lower right shows typical canal structure.

Typical fossil constituents of lower Glen Rose reefs, Red Bluff Creek, Bandera County, Texas.

Plate XI



(A) Comparison of a Glen Rose stromatolite (bottom) with modern one (top) collected from mangrove mudflat in Florida Bay, south Florida.



(B) Cross-section view of crenulated stromatolite with overhanging face. Locality is on Seco Creek, one-quarter mile north of Utopia road crossing, Medina County, Texas.

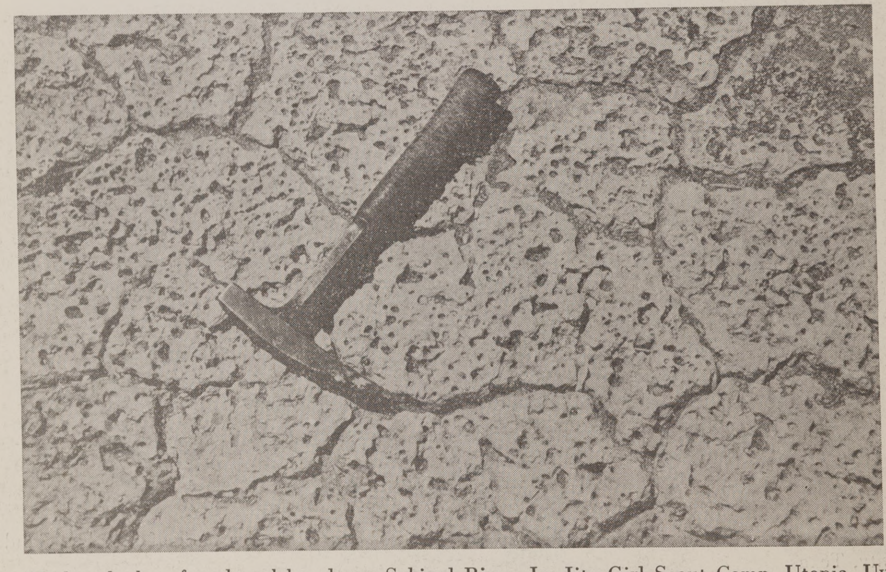
Detail views of algal heads in lower Glen Rose intertidal sequence.

(A) Rippled bar deposits. Rippled beds are typically present immediately below the algal deposits, but these are seen in overlying, lenticular bar deposits which thicken toward left of photograph. The ripple crests in this case wrap around the face of the bar as a probable result of wave refraction.

(B) Hummocky surface of stromatolitic algal deposits. Diverse morphological patterns of algal heads developed locally on this surface include low-relief domal colonies, long windrows, and irregular ridges.

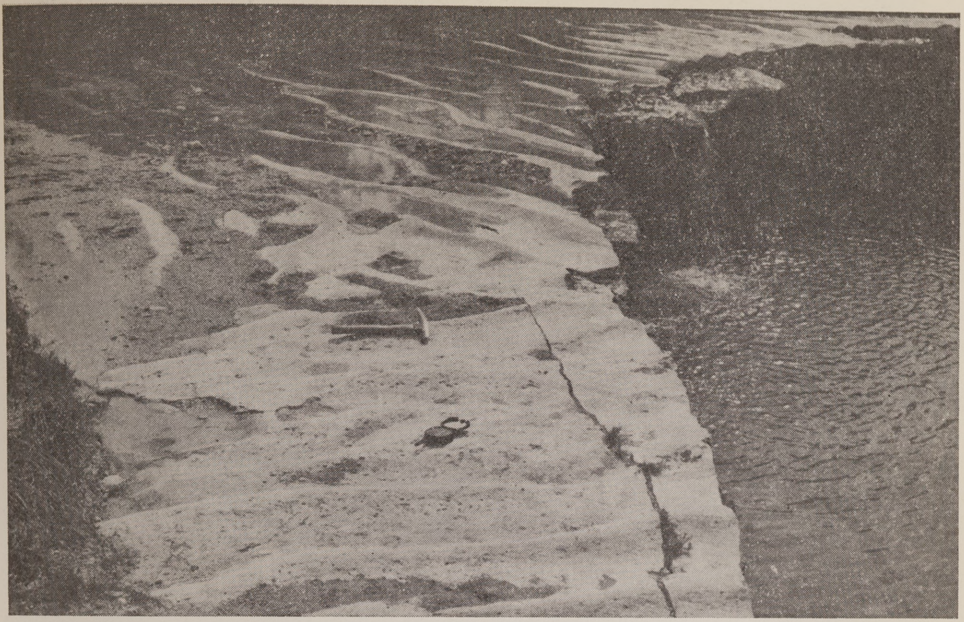
Lower Glen Rose intertidal deposits, Hondo Creek, three-quarters mile south of Tarpley, Bandera County, Texas.

(A) Surface bored by clams, Hondo Creek, three-quarters mile south of Tarpley, Bandera County, Texas. This surface is developed locally over the crest of rippled bar deposits shown in Plate 12, A.



(B) Mudcracked surface bored by clams, Sabinal River, La Jita Girl Scout Camp, Utopia, Uvalde County, Texas. Dinosaur tracks are also present on this surface.

Diagnostic sedimentary features of lower Glen Rose intertidal deposits. These features, which are present on initially "hard" surfaces, are attributed to subaerial exposure of the sea floor, perhaps during low tide.

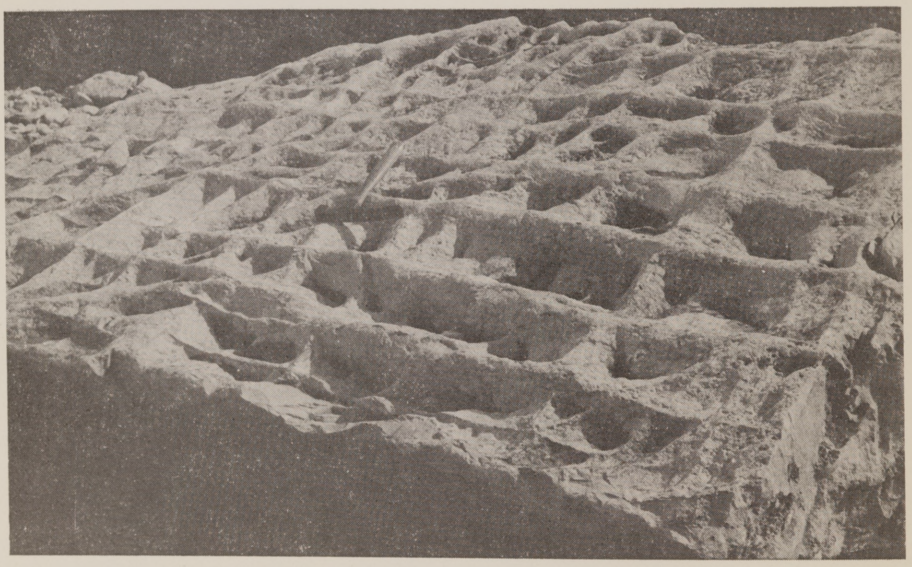


(A) Ripple marks in channel of Hamilton Creek, three-quarters mile east of juncture with Pedernales River, Travis County, Texas. The broadness, irregularity, and asymmetry of the ripples are attributed to a current origin.

(B) Casts of *Corbula martinae*, x2. Preferential orientation of the casts (parallel to bottom of page) is probably due to alignment by currents.

Typical features of reworked *Corbula* bed.

(A) Parallel joints and small faults in lime mudstone produced by settling attending removal of evaporites from underlying rubbly, contorted beds. Locality is on branch of Benton Creek, about 1 mile north of Medina, Bandera County, Texas.



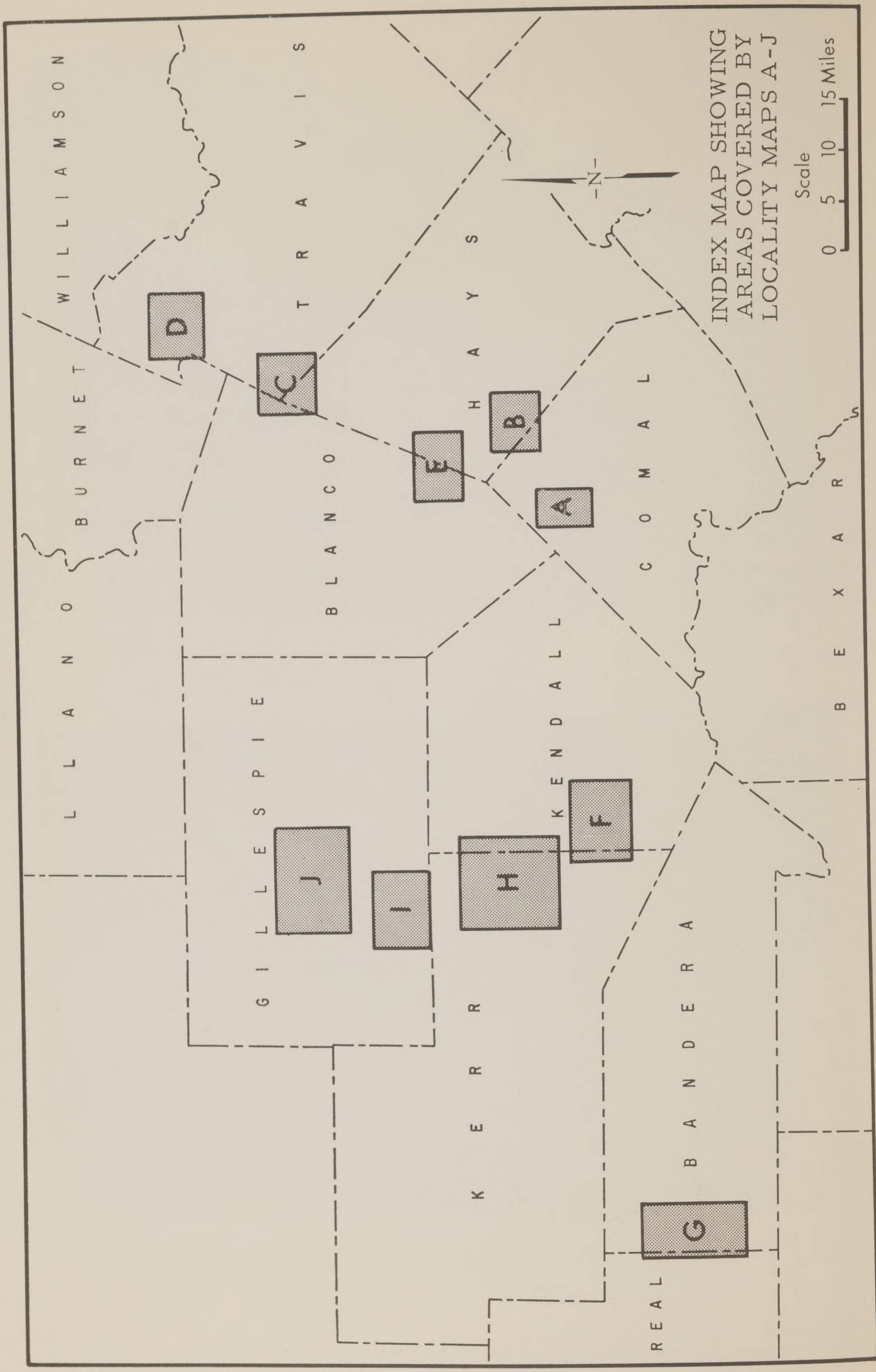
(B) Large slump block displaying boxwork structure formed by secondary deposits along intersecting joints and bedding planes. Locality is on Seco Creek, 1 mile north of Utopia road crossing, Uvalde County, Texas.

Vadose features of evaporite interval. The features are confined to a well-developed aquifer of ground-water circulation and are a result of collapse due to leaching of bedded evaporites.

APPENDIX

The stratigraphic sections of figures 9, 10, and 11 were constructed by piecing together individual measured sections for each major locality. Because the thickness of the deposits involved ranges up to 500 feet, several individual sections (as indicated by capital letters) were usually required to construct the composite section for each major locality. The individual sections making up the composites range up to a maximum of nine.

The following detailed locality maps are included in case the reader wishes to examine any of the individual measured sections. To determine the locality of any specific individual section, consult the insert locality map of the appropriate cross section and then refer to the indicated maps in the Appendix for the desired major locality. The individual sections are then shown on the major locality maps by dotted lines referenced by capital letters (such as Section D) and in many cases by the ranch or land owner.


INDEX MAP SHOWING
AREAS COVERED BY
LOCALITY MAPS A-J
Scale
0 5 10 15 Miles
N
WILLIAMSON
BURNET
LLANO
TRAVIS
BLANCO
HAYS
COMAL
GILLESPIE
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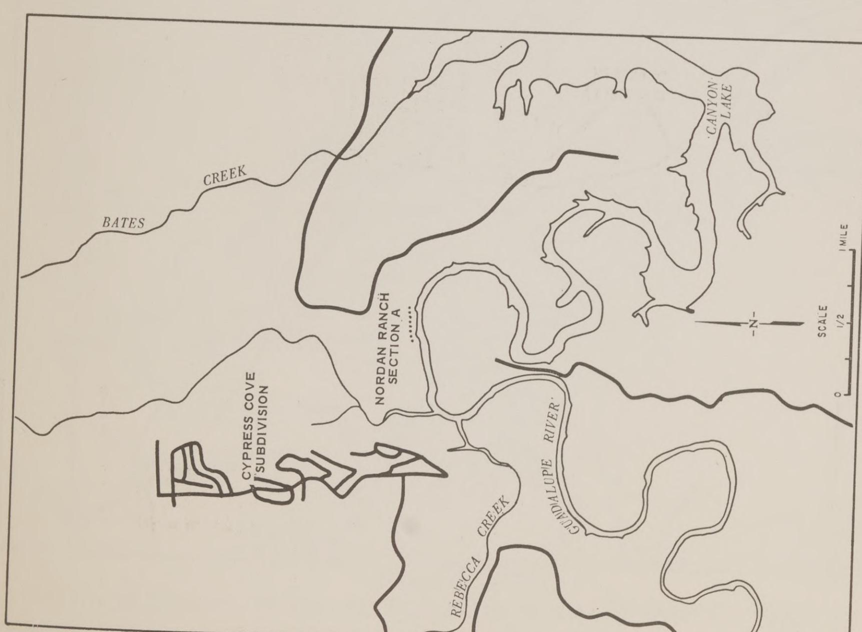
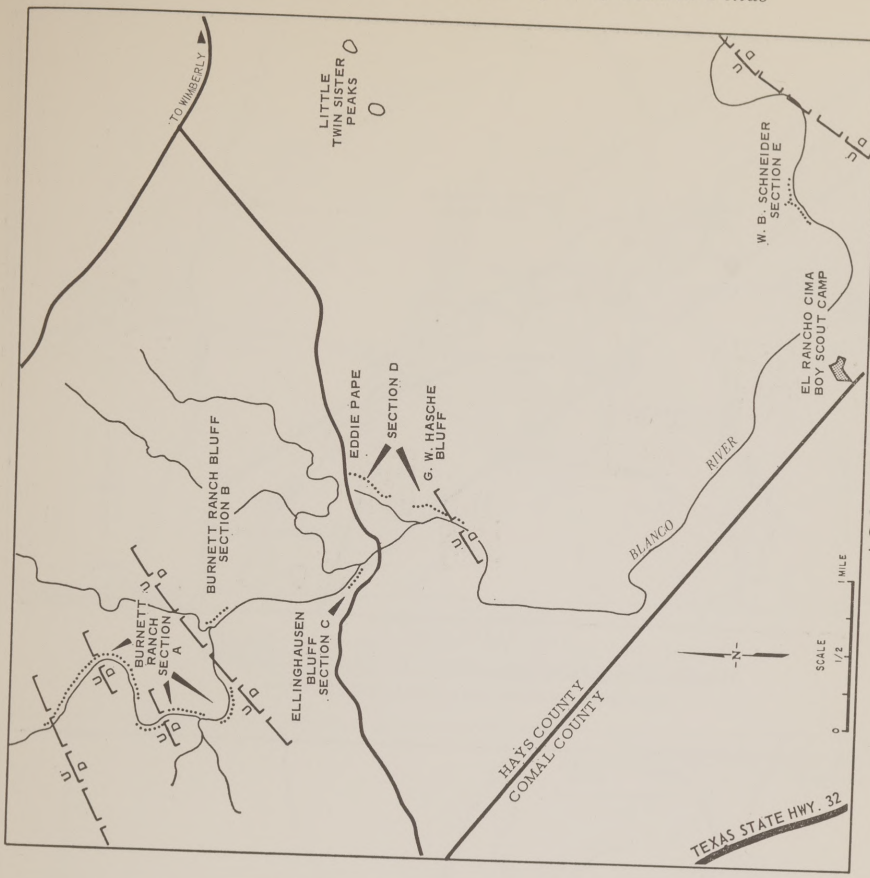
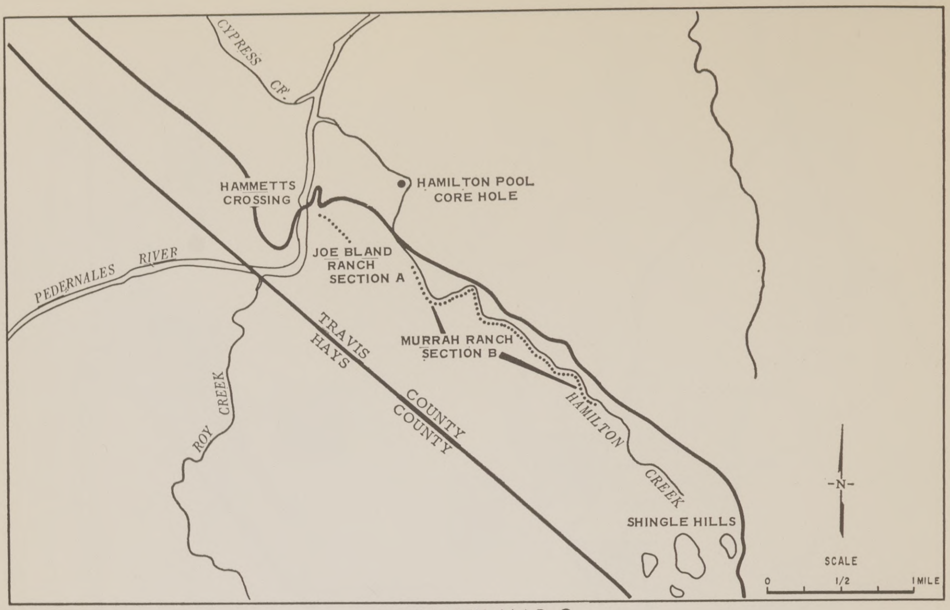


LOCALITY MAP A
GUADALUPE RIVER SECTION ④, COMAL COUNTY
(LOWER GLEN ROSE STRATIGRAPHIC SECTION)



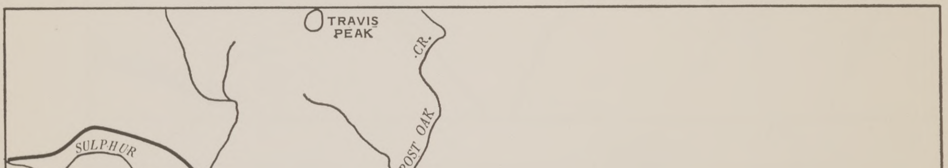
LOCALITY MAP B
BLANCO RIVER SECTION ③, HAYS COUNTY
(LOWER GLEN ROSE STRATIGRAPHIC SECTION)



LOCALITY MAP C

HAMILTON CREEK SECTION ②, TRAVIS COUNTY

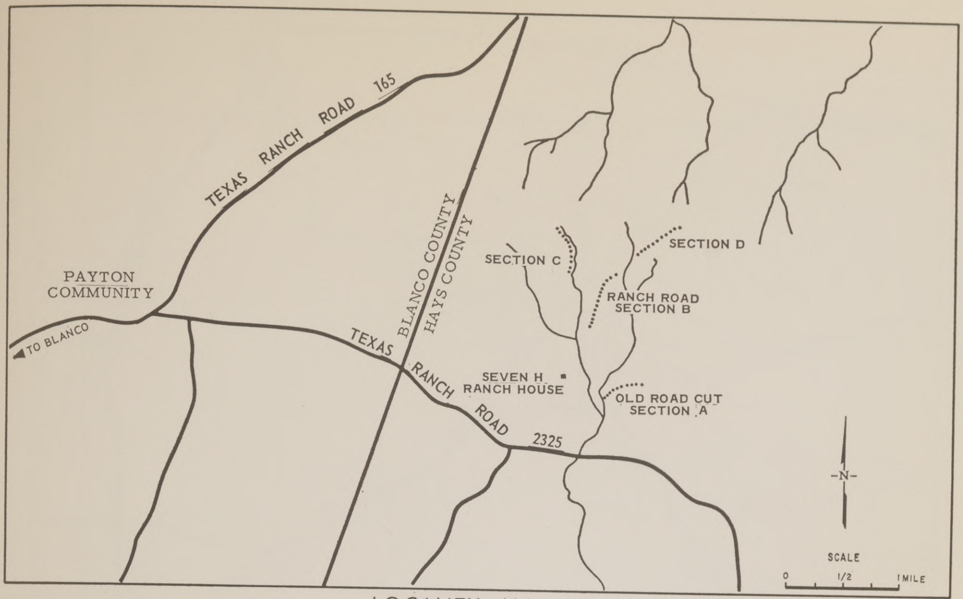
(LOWER GLEN ROSE STRATIGRAPHIC SECTION)



LOCALITY MAP D

COW CREEK SECTION ① AND BAR K RANCH SECTION ④, TRAVIS COUNTY

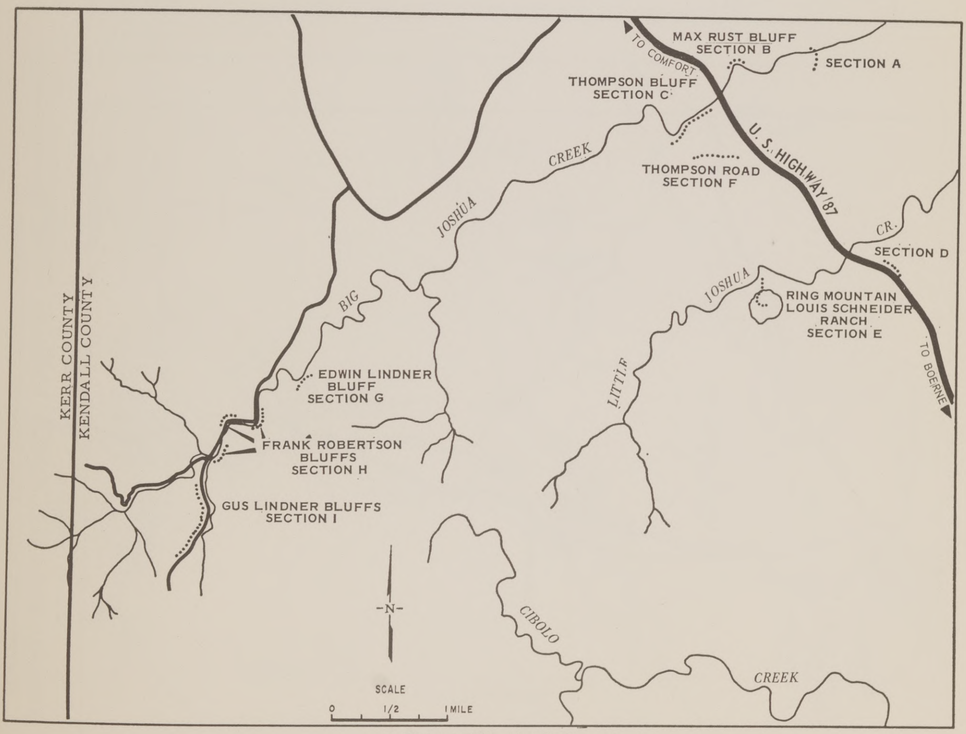
(LOWER GLEN ROSE STRATIGRAPHIC SECTION AND UPPER GLEN ROSE STRATIGRAPHIC STRIKE SECTION)



LOCALITY MAP E

SEVEN H RANCH SECTION ③, HAYS COUNTY

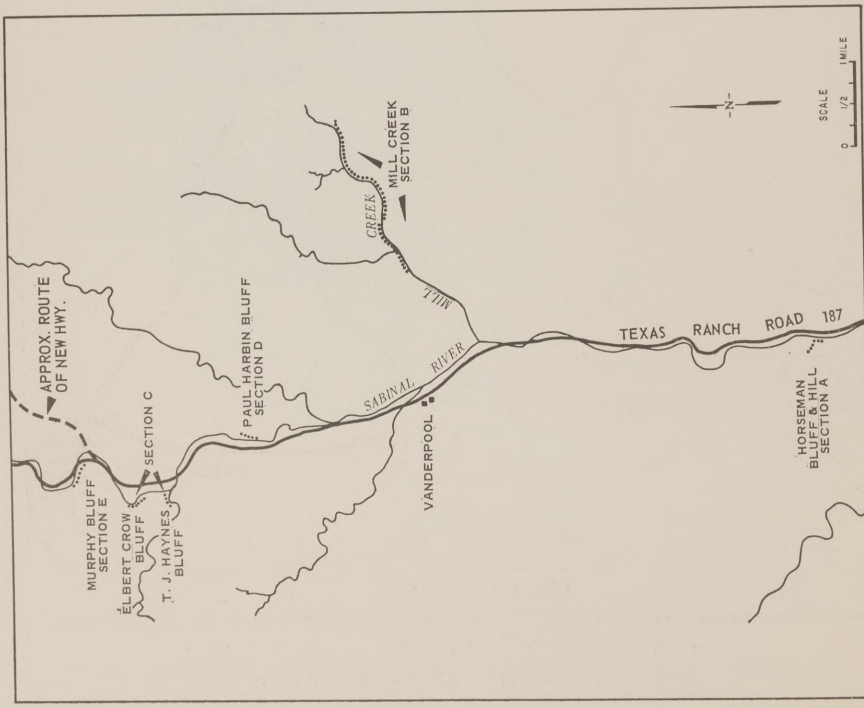
(UPPER GLEN ROSE STRATIGRAPHIC STRIKE SECTION)



LOCALITY MAP F

JOSHUA CREEKS SECTION ② AND ⑥, KENDALL COUNTY

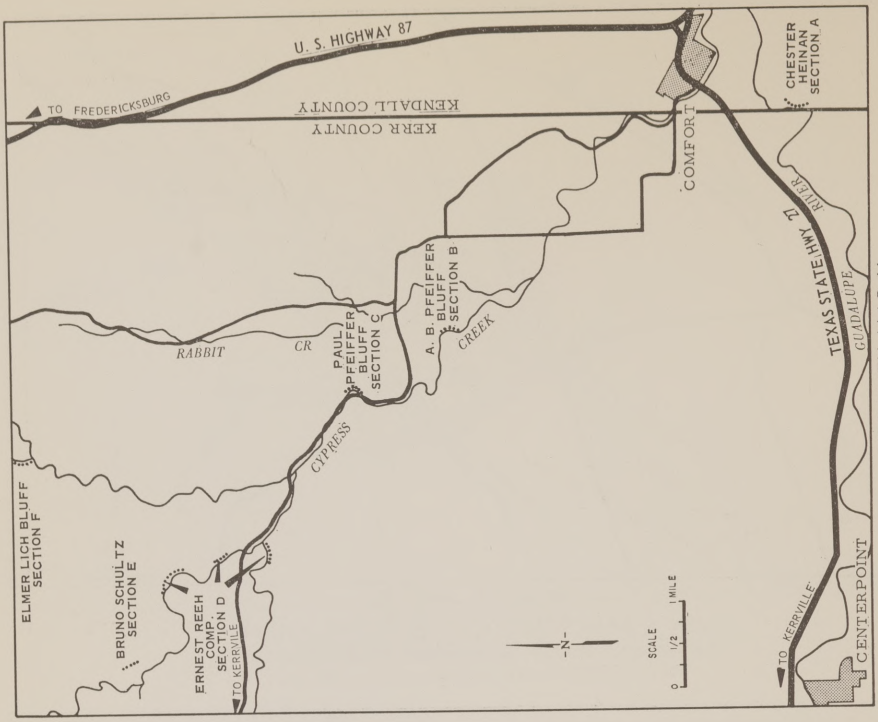
(UPPER GLEN ROSE STRATIGRAPHIC STRIKE AND DIP SECTIONS)



LOCALITY MAP G

SABINAL RIVER SECTION ①, BANDERA COUNTY

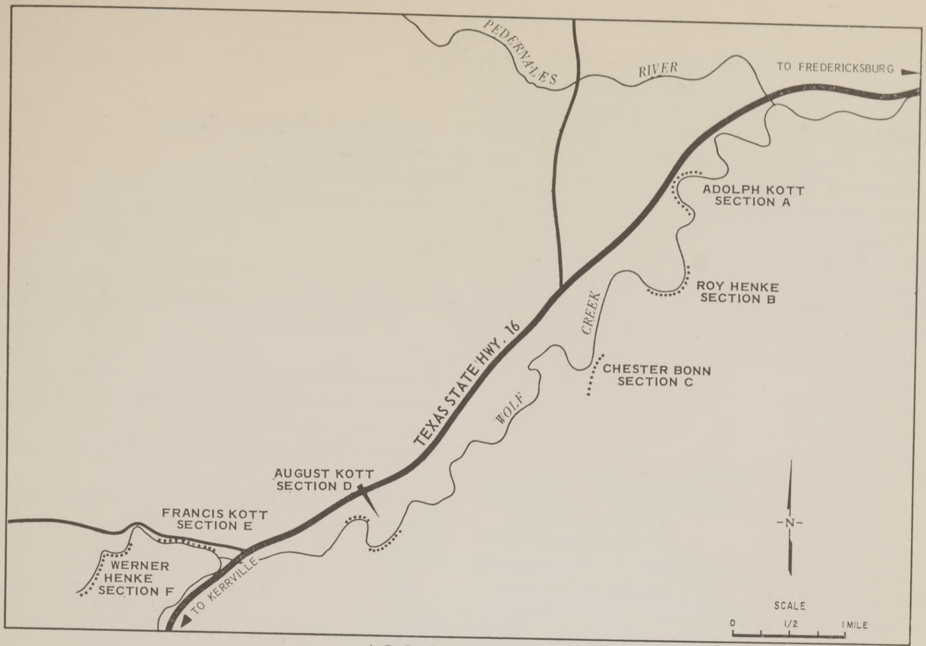
(UPPER GLEN ROSE STRATIGRAPHIC STRIKE SECTION)



LOCALITY MAP H

CYPRESS CREEK SECTION ⑤, KENDALL COUNTY

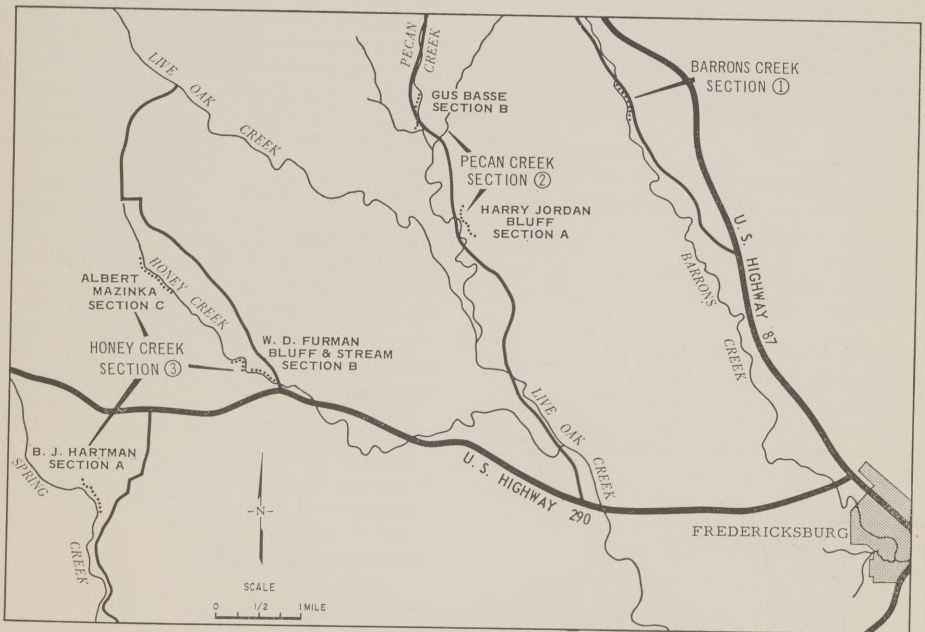
(UPPER GLEN ROSE STRATIGRAPHIC DIP SECTION)



LOCALITY MAP I

WOLF CREEK SECTION ④, GILLESPIE COUNTY

(UPPER GLEN ROSE STRATIGRAPHIC DIP SECTION)



LOCALITY MAP J

BARRONS CREEK SECTION ①, PECAN CREEK SECTION ②, AND HONEY CREEK SECTION ③, GILLESPIE COUNTY

(UPPER GLEN ROSE STRATIGRAPHIC DIP SECTION)

Index

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Watch line

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Packet 5

BUREAU OF ECONOMIC GEOLOGY

Report of Investigations No. 70

ADDENDUM TO PLATE I

The San Carlos Formation, Cox Sandstone, "Gulfian marine strata," Boquillas Formation, and Javelina Formation are Cretaceous in age. The Black Peaks Formation (Big Bend National Park) should be read as Paleocene in age. The following age assignments were made or proposed while the present report was in press: Wilson et al. (1968) placed the Oligocene-Eocene boundary at the top of the Buckshot Ignimbrite in the Vieja Group (Rim Rock Country) and Garren Group (Van Horn Mountains and vicinity); Wilson (in press) placed the Oligocene-Eocene boundary within the Pruett Formation (Buck Hill quadrangle, southern Davis Mountains).

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__________, Twiss, P. C., DeFord, R. K., and Clabaugh, S. E. (1968) Stratigraphic succession, potassium-argon dates, and vertebrate faunas, Vieja Group, Rim Rock Country, Trans-Pecos Texas: Amer. Jour. Sci., vol.266, pp. 590-604.

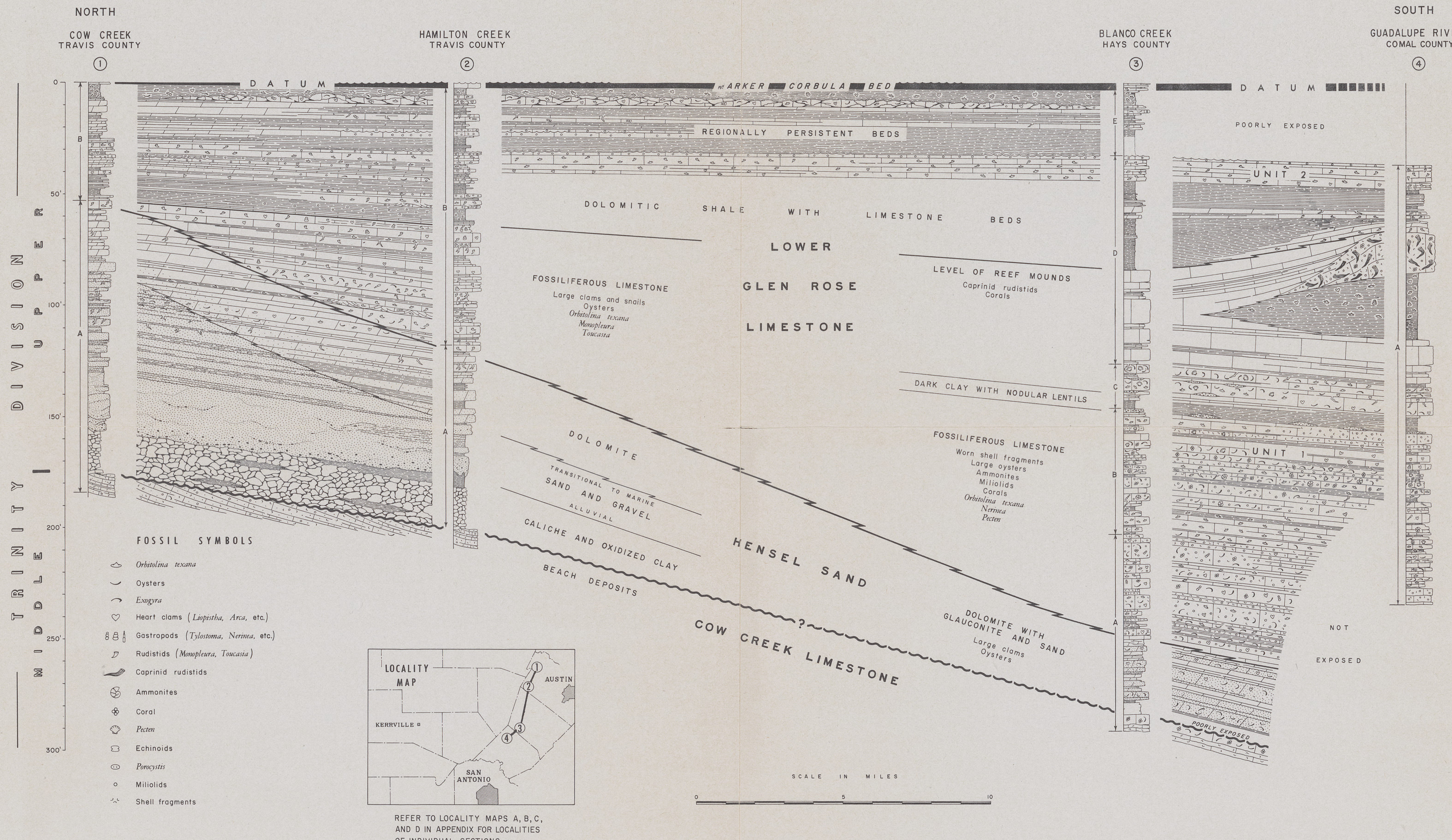

FIG. 9. Stratigraphic section of lower Glen Rose deposits.

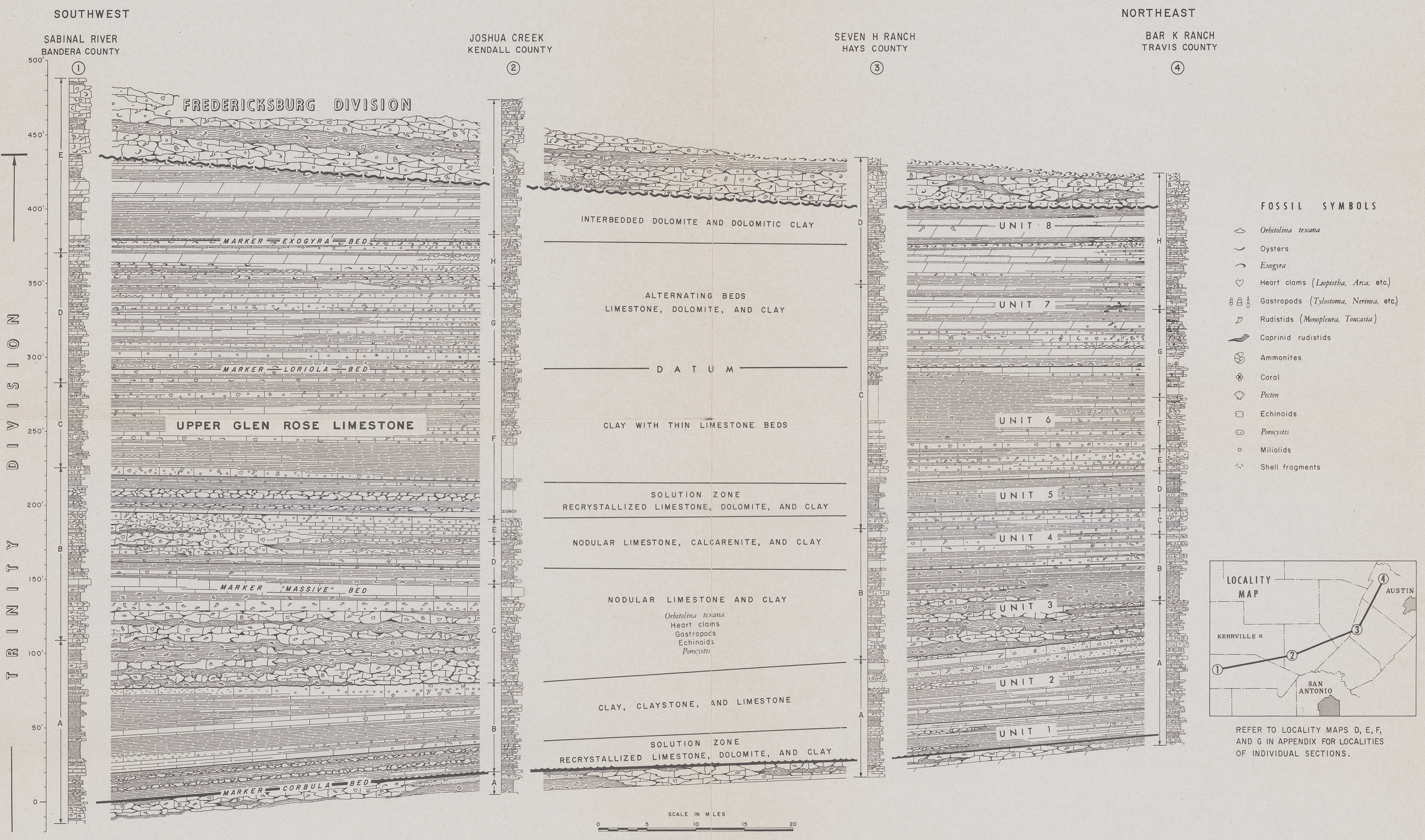

Fig. 10. Stratigraphic strike section of upper Glen Rose deposits.

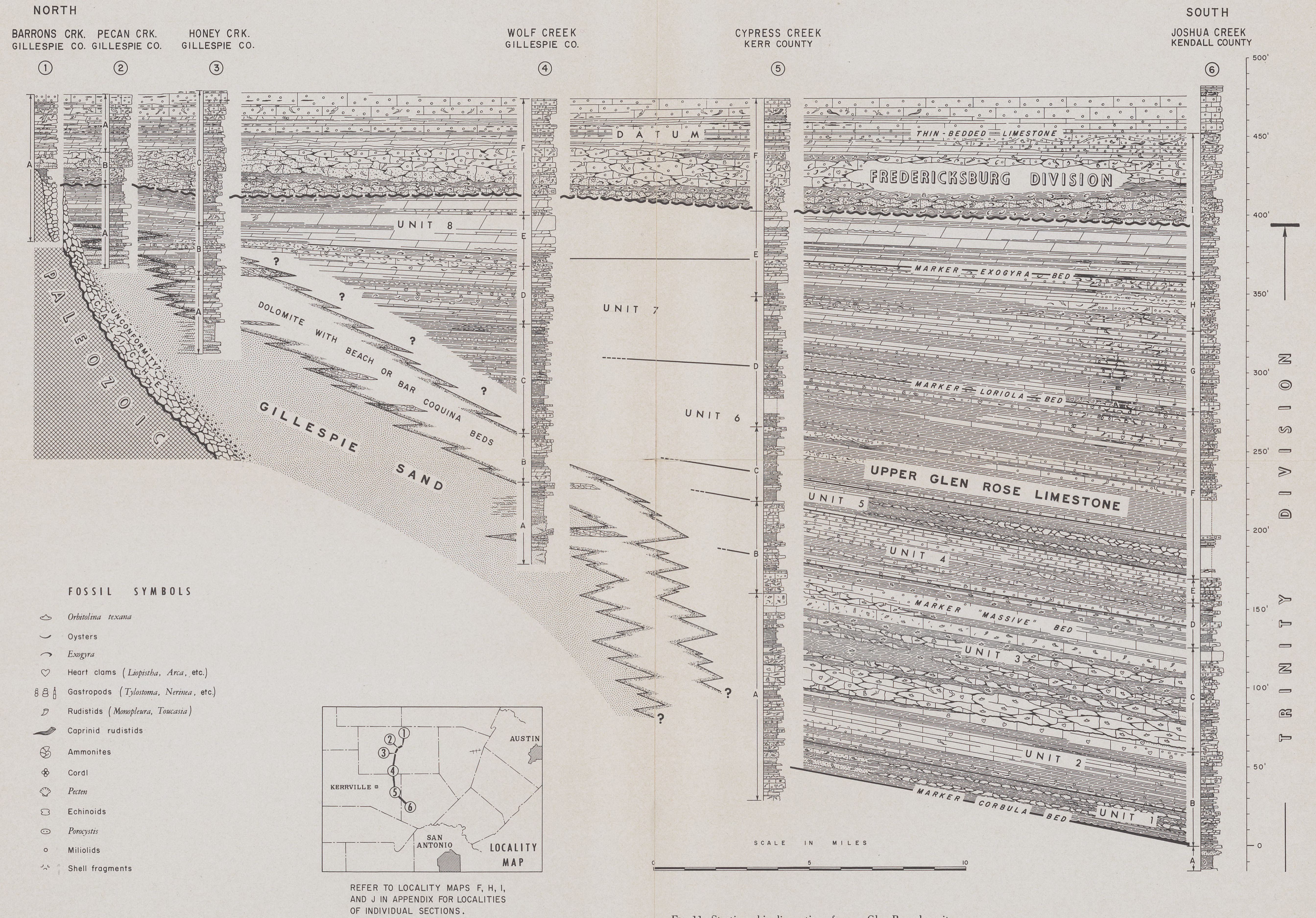

Fig. 11. Stratigraphic dip section of upper Glen Rose deposits.